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JUL 78 J L ROSE, G P SINGH N68335-77-C-0556

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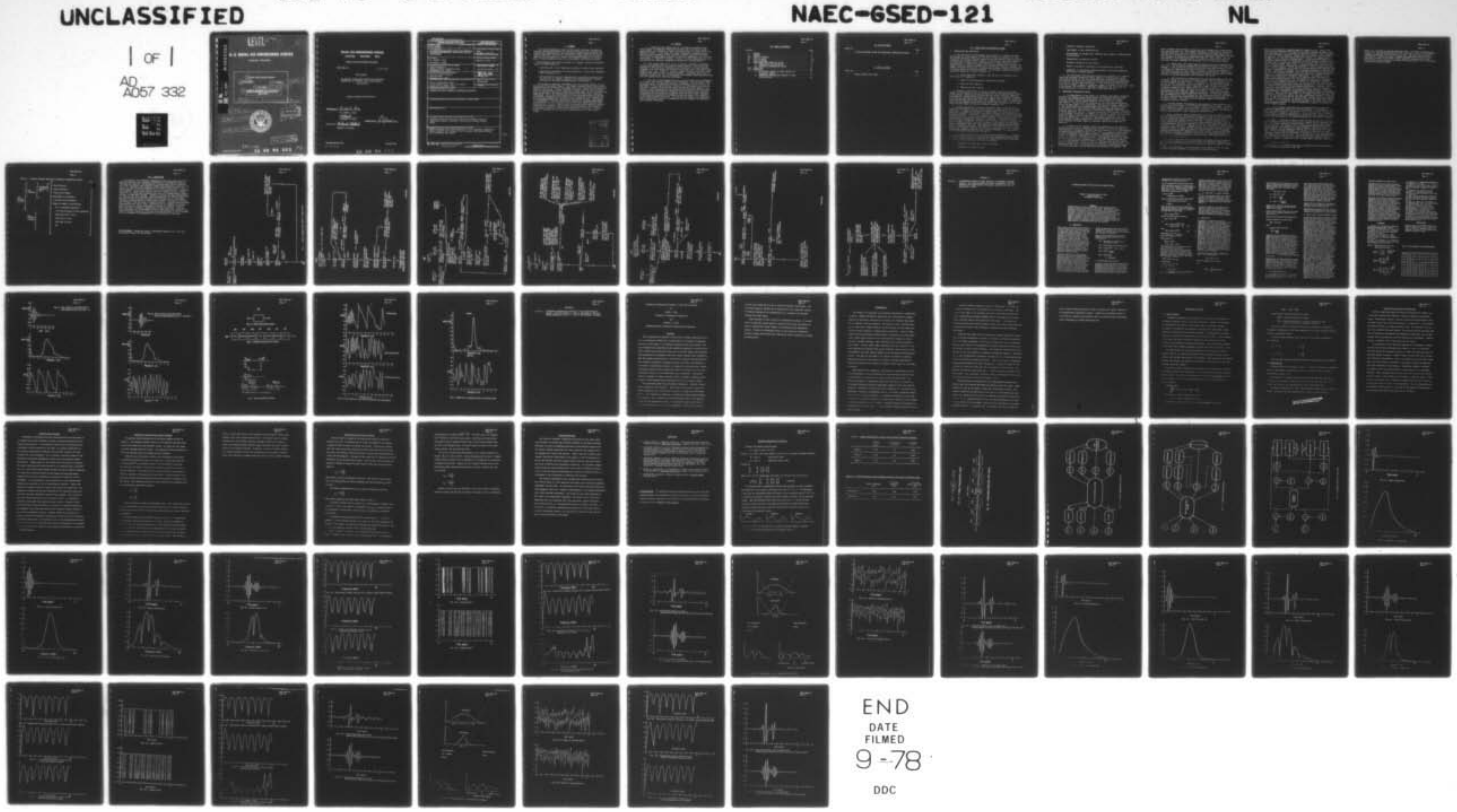

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19 GROUND SUPPORT EQUIPMENT DEPARTMENT

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NAVAL AIR ENGINEERING CENTER

LAKEHURST, NEW JERSEY 08733

GROUND SUPPORT EQUIPMENT DEPARTMENT

NAEC-GSED-121

21 July 1978

FINAL REPORT

AN ADAPTIVE ACCEPT-REJECT MODULE FOR TRANSDUCER EVALUATION AND POTENTIAL FLAW CLASSIFICATION APPLICATIONS

AIRTASK A3400000/051B/8F41461400

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Advanced concepts and various approaches on the transducer compensation module along with the concepts on an intelligent flaw detector module are presented in this report.

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I. SUMMARY

The required feasibility study for the project entitled, "An Adaptive Automatic Accept-Reject Module for Transducer Evaluation and Potential Flaw Classification Applications", was conducted at Drexel University during the contract year 1977. This part of the research program serves as an initial phase in the development of a larger, more expanded program on the development of detailed specifications for an intelligent flaw detection system.

An intelligent flaw detection system is a computer controlled ultrasonic inspection system capable of:

- indicating the correct inspection procedure for parts being inspected;
- analyzing the transducer and system operation to insure that meaningful data is acquired; and
- interpreting the data and compensating for any system variations that may occur due to changes or aging of the transducer and/or couplant variations or any other inconsistencies in the system.

The problem of transducer compensation was the principal subject of study during this initial phase, Phase I. The results obtained using a deconvolution algorithm were not as accurate as desired due to both "noise" and nonlinearities present in the system. A rigid "GO/NO-GO" acceptance criteria for the transducer was therefore specified to establish a linear range for which compensations might be applicable, and deconvolution analysis used after such a range was established. Due to the limited success of the above approaches, the problem of transducer compensation is attacked from the viewpoint of intelligent flaw detector program rather than of solving a very general problem. The transducer compensation is neither essential nor required for thickness measurement or flaw detection. It is critical, however, for flaw characterization and/or classification. Out of a feature vector containing several important features describing the transducer, only relevant ones pertaining to the problem will be employed along with a deconvolution algorithm for future work. Further studies in this area will be carried out during Phase II of the research project.

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II. PREFACE

A. A feasibility and design study on "An Adaptive Automatic Accept-Reject Module for Transducer Evaluation and Potential Flaw Classification Applications", was conducted at Drexel University under U.S. Navy Contract No. N68335-77-C-0556. It was found that linear mathematical modeling used for describing and evaluating various transducer transfer functions was useful for solving the very complex problem of transducer compensation, but in a very limited way. A "GO/NO-GO" acceptance criterion for the transducers had to be specified before employing compensation mathematical modeling analysis.

B. This concept made use of a list of specific transducer performance features as measured from the ultrasonic signal features. The feature list consisted of such items as transducer center frequency, 6 dB down frequency bandwidth, near field value, dB variation within near field, a measure of beam symmetry, etc. The "GO/NO-GO" concepts compared features with a list found suitable from advanced flaw or material analysis. Percentage deviations of individual items on the list are determined from feedback mechanisms associated with the classification algorithm development.

C. This part of the program serves as an initial phase in the development of a larger, more expanded program on the development of an intelligent flaw detection system, the transducer playing a tremendously critical role in the development of the complete system. Basically, an intelligent flaw detection system is a computer controlled ultrasonic inspection system capable of indicating correct inspection system procedures, specifying and checking transducer and couplant performance, obtaining useful ultrasonic data, providing compensation for any system and transducer variation and finally, employing a classification algorithm for determining flaw size and/or flaw characteristics and/or material variations. The system will operate on an interactive basis, allowing the operator to communicate with the computer in conducting the ultrasonic examination.

III. TABLE OF CONTENTS

IV. LIST OF TABLES

Table No. Page

V. LIST OF FIGURES

Figure No. Page

VI. INTELLIGENT FLAW DETECTION SYSTEM

A. INTRODUCTION AND MOTIVATION.

1. The function of an intelligent flaw detector is to combine the speed and accuracy of a minicomputer with the data acquisition capability of a sophisticated ultrasonic inspection system and various advanced signal processing techniques into a single system capable of conducting an inspection sequence including data evaluation with a minimum amount of human intervention and system variation. Total intelligent flaw detection systems are necessary and needed because of inherent limitations of conventional ultrasonic systems. For example, the potential success of conventional ultrasonic inspection techniques, to a large extent, is operator dependent. An ultrasonic inspector while performing an inspection is usually required to

a. Select the proper frequency, type and size of transducer from a wide variety of transducers,

b. Select the most appropriate inspection technique,

c. Carry out the inspection,

d. Evaluate the test results.

2. Evidently, the success of such an ultrasonic inspection critically depends on the experience, skills, working conditions and psychological factors of the operator. Many times different operators select different inspection techniques for inspecting the same part and come up with contradictory results. It is a rather well established fact that, compared with a computer, humans are quite poor at handling and evaluating the ultrasonic test data. In other words, even a skilled operator cannot positively assess flaw criticality and its quantitative relationship with fracture mechanics theories, etc.

3. Another problem with ultrasonic inspection today, is associated with transducer performance evaluation and assuring the repeatability of the ultrasonic test. It would be desirable to compare output on a given day with a particular instrument and operator with results obtained from some earlier data acquisition period. A repeatable ultrasonic test result is definitely important and needed in order to solve many complex problems of flaw characterization and classification using pattern recognition algorithms. Preliminary research indicated that an invariable ultrasonic input function from a broad band transducer is highly desirable to obtain the highest, reproducible and meaningful index of performance for flaw classification purposes employing sophisticated pattern recognition algorithm. This generally is not possible due to various reasons: for example, changing the controls on pulser-receiver units, transducer aging, transducer wear and tear, couplant thickness, pressure applied to hold transducer during contact testing, etc.

4. The problems outlined above are particularly addressed in our proposal on "An Intelligent Flaw Detector Specification and Feasibility Study for the U.S. Navy", with an accent on automation utilizing microprocessor technology. The features of an intelligent flaw detector include:

. Increase of testing speed (reduced downtime)

. Elimination of human failures

- Automatic transducer evaluation
- Improvement of test reproducibility
- Establishment of optimum test conditions with respect to flaw detection and evaluation
- Comprehensive recording of results
- Automatic evaluation of test results
- Merger of ultrasonic technology with microprocessor technology
- Capability of carrying out advanced analysis in pattern recognition and computer learning analysis

5. The intelligent flaw detection system will, therefore, be a computer controlled ultrasonic inspection system capable of indicating the correct inspection procedure for the part being inspected, analyzing the transducer and operation of the system to insure that meaningful data is being acquired, interpreting the data and compensating for any system variations that may occur due to change or aging of transducer, change of couplant or any other change in the system. The problem of transducer compensation was the subject of study during Phase I (contract year 1976-77) and presented next.

B. TRANSDUCER COMPENSATION MODULE

1. An investigation on the subject of transducer performance evaluation entitled, "An Adaptive Accept-Reject Module for Transducer Evaluation and Potential Flaw Classification Applications", was carried out at Drexel University under Contract Number N68335-77-C-0556 during the contract year 1976-77. The motivation for carrying out this work task was guided by one of the final goals in the Intelligent Flaw Detection Scheme, namely, that of flaw classification with minimum human intervention. Research, to-date in the area of flaw classification using pattern recognition algorithms indicates that it is very essential to use similar ultrasonic input functions to obtain meaningful results. It may be pointed out that a number of variables in an ultrasonic system such as changing the controls on pulser-receiver units, transducer aging, transducer wear and tear, couplant thickness, etc., all affect the RF waveform. A transducer compensation module was, therefore, envisioned which could eliminate such critical parameters as type of transducer, couplant thickness, aging of transducer, day-to-day variations in pulser etc.

2. A portion of the research carried out during the initial phase was presented in the form of a research paper, entitled, "On Selected Aspects of Phase Analysis in Ultrasonic Testing", which was presented at the 11th Symposium on Nondestructive Evaluation, April 20-22, 1977 at San Antonio, Texas and is included in Appendix A for reference purposes. Mathematical details on the subject of transducer compensation using a deconvolution algorithm and the concept of "GO/NO-GO" acceptance criterion are explained in the above paper. Mathematical details were implemented on a PDP-11/05 minicomputer using a Biomation 8100 analog to digital converter, Tektronix 4015 graphics display package, Aerotech UTA-2 pulser and gate and Tektronix 7704 oscilloscope. The mathematical details of the deconvolution algorithm, although fairly simple in concept, does cause various implementation problems on a computer. One

has to surmount such problems as division by zero, taking care of phase angles and complex division etc. The computer program was checked against theoretical transfer functions.* Excellent results were obtained, strongly supporting the possibility of elimination of ultrasonic system variables as mentioned previously. The usefulness of deconvolution algorithm using real flaws, however, was very much limited. The problem turned out to be much more complicated using conventional ultrasonic equipment and procedures due to the following reasons.

a. Quite often, the pulser-receiver characteristics are dependent upon each other. The RF waveform changes when attenuation settings on the pulser are changed. It was found that the pulser needed electronic modifications in order to separate its characteristics from the receiver. Technical discussions in that regard are under way with several instrument manufacturers. Separation is crucial in establishing reliable compensation procedures and meaningful transfer functions of various components in an ultrasonic test system.

b. The deconvolution algorithm has the underlying assumption that the ultrasonic system, in this case, is a linear system. Various components of the ultrasonic system are shown in Fig. 3 of Appendix A. The discrepancy in the results obtained, therefore, can be attributed to the nonlinearities present in the system. It was then decided to establish a range, if any, in which an ultrasonic system acts as a linear system and develop a "GO/NO-GO" acceptance criterion on certain signal features, as an example, center frequency, 6dB down bandwidth, pulse duration, number of cycles, etc. along with the mathematical deconvolution algorithm mentioned previously. It was found, however, that implementation of such a program was very tedious and could not be carried out due to insufficient feedback from the algorithm and the large number of variables involved. Real test flaws are required to make the "GO/NO-GO" acceptance criterion a reality.

3. Although somewhat discouraged by this approach, it was decided to reconsider the overall goals of the intelligent flaw detector program. The transducer compensation concept could be further utilized once the overall specifications for an intelligent flaw detector were determined. Some of the important design considerations for such a system are reviewed below.

4. First, a general purpose program which would guide an operator through selecting a proper probe, performing the inspection on any part and evaluating the test result was evaluated for its potential application in our project. A careful engineering analysis revealed that such a computer program would be rather tedious and unsuitable for solving simple inspection problems, besides the implementation into a microprocessor as a field instrument may become very difficult, if not impossible. Keeping in mind the final goal of a microprocessor inspection module for every different problem, a more basic approach was adopted. Flowchart concepts in Figure 1* present an initial design for an intelligent flaw detection system with emphasis on the first step of transducer selection. The cumulative ultrasonic inspection problem can be divided into several categories, e.g., thickness measurement, flaw detection, flaw classification in

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*Portions of this work will be presented at the Spring meeting of ASNT in New Orleans in a paper by J. Rose and M. Avioli on "Transducer Compensation of Value in Flaw Classifications" and is attached for reference purposes in Appendix B.

*Note that the module concept flowcharts can be assembled into one large flowchart by matching numbers contained on the individual pages.

metals, bond inspection, composite material inspection, etc. Each of the above mentioned categories are treated as different problems as shown in the charts and may result in a different microprocessor module. These flowcharts are based on general ultrasonic concepts and can be modified for each part to be inspected. A flaw detection microprocessor module, for example, may be designed for use on several different parts. As mentioned previously, the flowcharts presented here are preliminary and rather general in approach and are meant only to explain the concept of an intelligent flaw detector in principle. Three problems, namely that of thickness measurement, flaw detection and flaw classification in metals are presented in order to explain the principle. Similar diagrams could be made for solving various other important NDE problems. Flowcharts are presented for thickness measurement, flaw detection, and flaw classification problems. The intelligent flaw detection system will operate on an interactive basis allowing the operator to communicate with the computer in conducting the ultrasonic examination. The operator in this inspection procedure has to determine the inspection mode, determine the material and thickness class, etc., and physically carry out the inspection. Notice that the algorithm will aid the operator in appropriate transducer selection and performance evaluation. In the case of the flaw detection and thickness measurement problems, transducer compensation is neither critical nor required hence simplifying the examination procedure. Moreover, the reject transducers from flaw classification could probably be used for thickness measurement producing possibly a considerable economic savings. Hence, the overall problem of transducer compensation and acceptance could be considerably simplified. This will not only result in the simpler algorithm and hence more economical microprocessor modules, but also considerable savings in inspection time. It may also be pointed out that automatic couplant selection, couplant check and data evaluation will be possible using an intelligent flaw detection algorithm. It is worthwhile mentioning that many of the boxes in the accompanying diagrams denoting 'D', will be determined in Phase II and Phase III of the research program.

5. In the flowchart describing the flaw classification program, the transducer compensation problem is the most important. The following is proposed and being evaluated at the present time in order to solve the very complex problem of transducer compensation. Out of a feature vector containing several important features describing the transducer, only relevant ones will be evaluated pertaining to the problem along with the deconvolution algorithm.

6. Table I illustrates a feature vector that may be used for transducer characterization purposes when solving a more general kind of inspection problem. For solving a specific problem, however, only a few relevant features may be evaluated. For example, for the thickness measurement problem the features may be pulse duration and center frequency. The specifications on these features, for this particular problem, may be within, say, 10-15 percent. For flaw detection problems such features as pulse duration, center frequency, Fresnel zone and beam angle of divergence, could be evaluated, the specs again are not very critical. For a problem like 23 flaw classification* study, however, the feature vector may contain 6db down frequency profile bandwidth, number of depressions in the 4-6 MHz region, kurtosis, number of

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*Rose, J.L., "A 23 Flaw Sorting Study in Ultrasonics and Pattern Recognition," Materials Evaluation, July 1977.

peaks, etc., besides the features mentioned above. The specs now become very critical for this problem and may be within 5 percent if only a rigid "GO/NO-GO" transducer acceptance criterion were to be used. The spec limits on these features may be related by using a feedback mechanism from the deconvolution algorithm, in order to establish a linear range for the algorithm to work. Further work in this area will be carried out during Phase II of the Intelligent Flaw Detection Module Program.

Table I - A Typical Feature Vector for Transducer Compensation Module

Flaw Sorting Problem

Flaw Detection

Thickness measure-ment

Pulse Duration

Center Frequency

Fresnel Zone Length

Beam Angle of Divergence

6 db Down Center Frequency

Number of Peaks in the Waveform

No. of Spectral Depressions

6 db Down Frequency Profile Bandwidth

Bond Strength Problem

Amplitude Time of Pulse

Rise Time of Pulse

Fall Time of Pulse

Etc.

VII. CONCLUSIONS

In conclusion, the transducer compensation problem has been found to be much more difficult than originally anticipated if a generalized solution technique were desired. The problem will be approached from the viewpoint of a total intelligent flaw detector program with compensation treated in the future in a specific manner depending on the problem being studied. This report presents a first step towards such an intelligent machine. Flowcharts are necessary. These charts could be used as a teaching aid for training inspectors, for developing laboratory facilities, for establishing a specific solution for many Navy problems. Automatic recording and data interpretation are feasible with such a system. Flaw classification or further analysis of any kind that may be deemed necessary can be carried out at a later date. Transducer characterization is very problem oriented, resulting in considerable savings in time and money if handled carefully. Couplant checks are made automatically from time to time. Algorithms will be designed for minimum human intervention, proper transducer and inspection technique selection, data acquisition, transducer compensation and data evaluation. Although these algorithms will be developed on PDP-11 minicomputer and Biomation 8100 analog-to-digital converter, an initial study during Phase III of the program will be undertaken for implementation into microprocessor technology.

ACKNOWLEDGMENTS - Thanks are given to Krautkramer Branson, Inc., for their minicomputer support of this project.

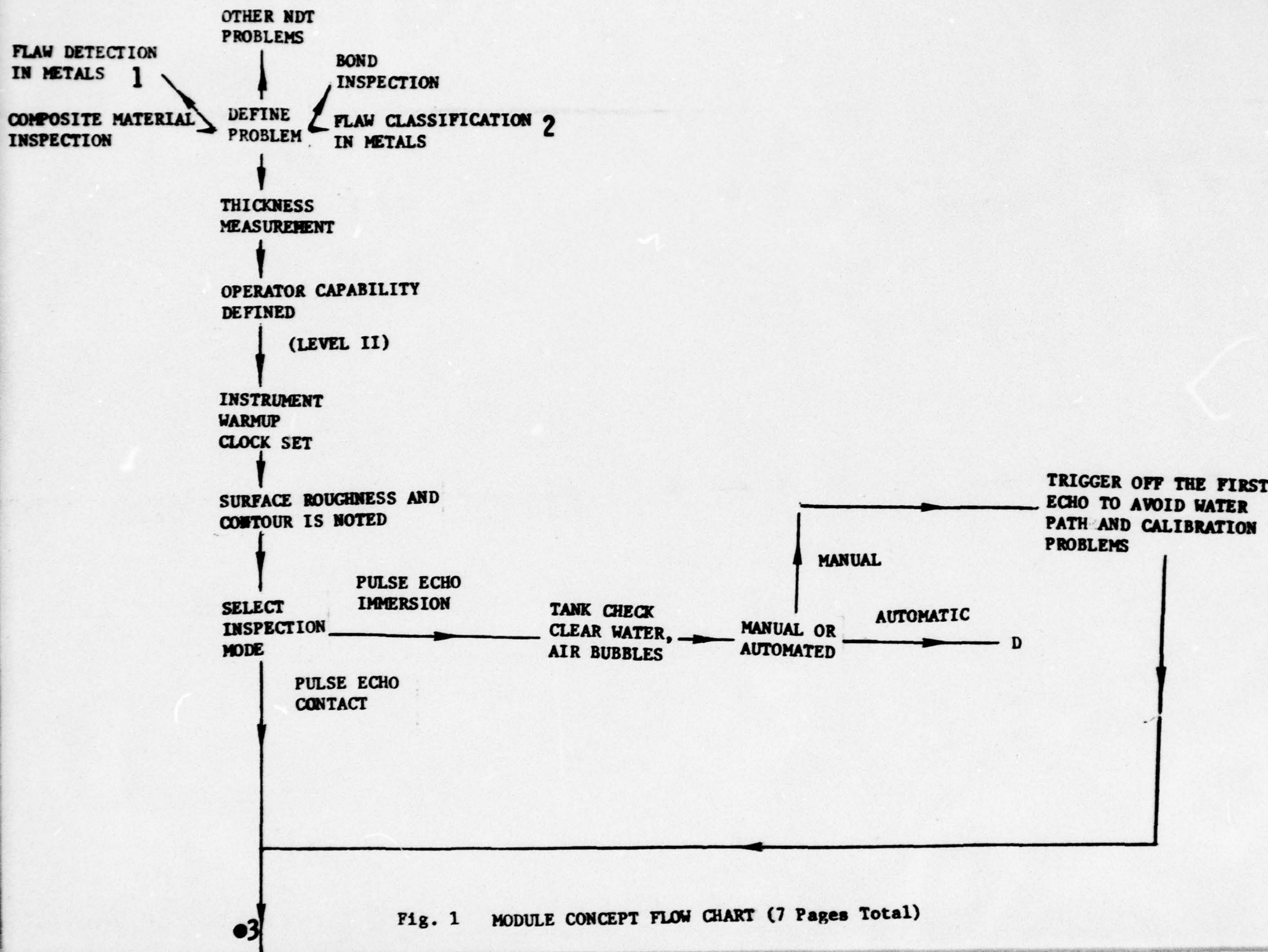
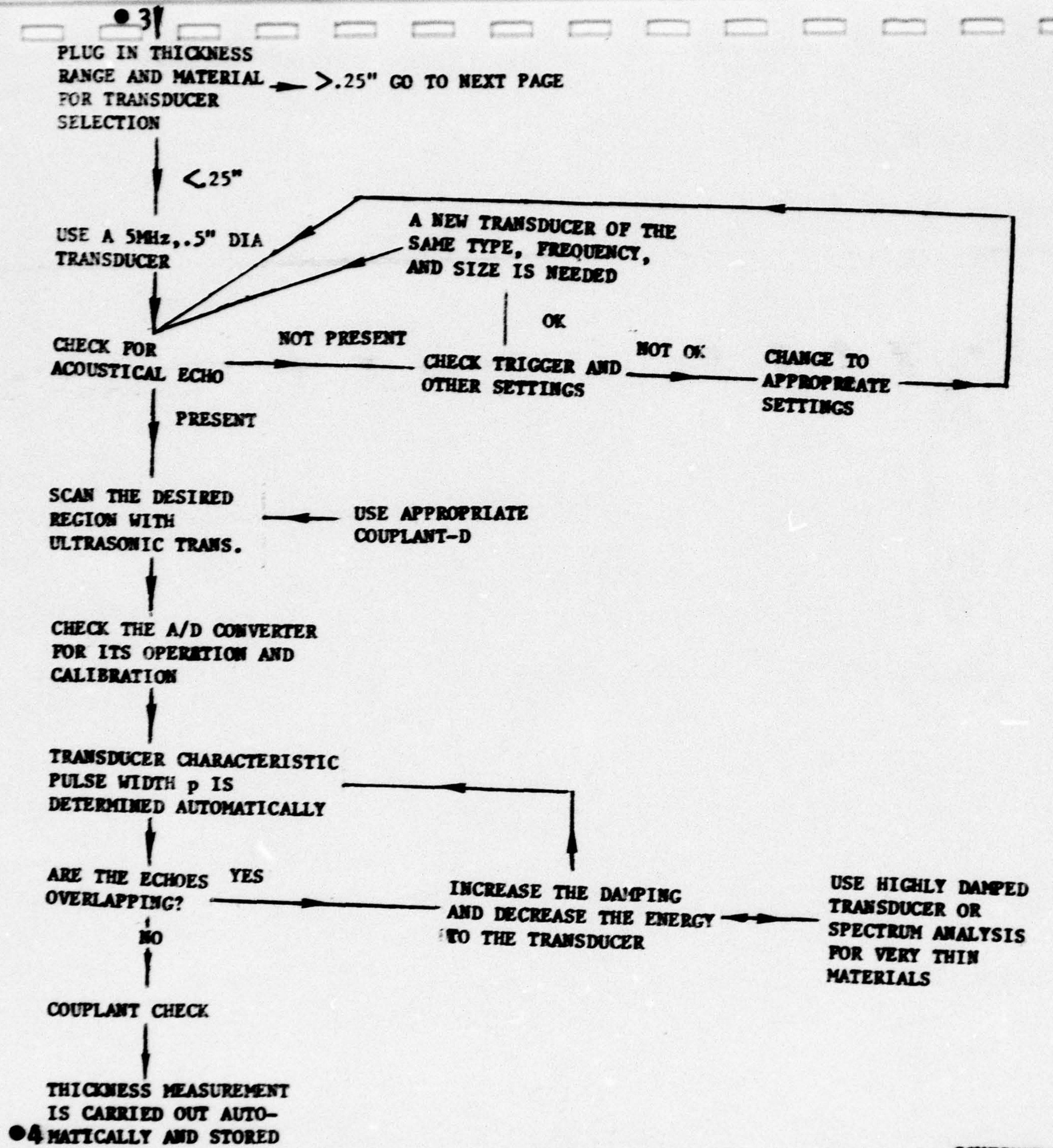
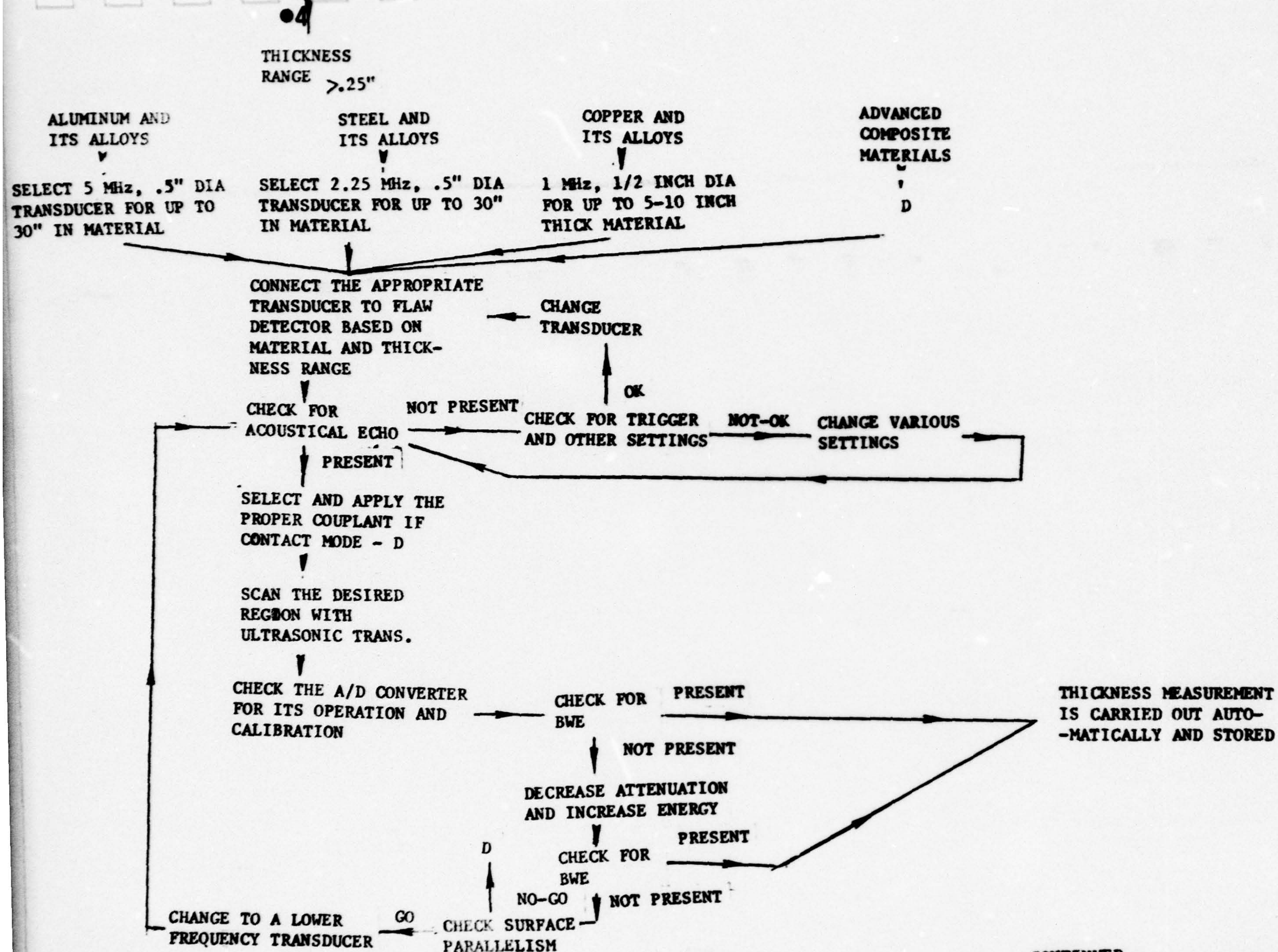


Fig. 1 MODULE CONCEPT FLOW CHART (7 Pages Total)


3
PLUG IN THICKNESS RANGE AND MATERIAL FOR TRANSDUCER SELECTION
>.25" GO TO NEXT PAGE
<.25"
USE A 5MHz,.5" DIA TRANSDUCER
A NEW TRANSDUCER OF THE SAME TYPE, FREQUENCY, AND SIZE IS NEEDED
OK
CHECK FOR ACOUSTICAL ECHO
NOT PRESENT
CHECK TRIGGER AND OTHER SETTINGS
NOT OK
CHANGE TO APPROPRIATE SETTINGS
PRESENT
SCAN THE DESIRED REGION WITH ULTRASONIC TRANS.
USE APPROPRIATE COUPLANT-D
CHECK THE A/D CONVERTER FOR ITS OPERATION AND CALIBRATION
TRANSDUCER CHARACTERISTIC PULSE WIDTH p IS DETERMINED AUTOMATICALLY
ARE THE ECHOES OVERLAPPING?
YES
INCREASE THE DAMPING AND DECREASE THE ENERGY TO THE TRANSDUCER
USE HIGHLY DAMPED TRANSDUCER OR SPECTRUM ANALYSIS FOR VERY THIN MATERIALS
NO
COUPLANT CHECK
THICKNESS MEASUREMENT IS CARRIED OUT AUTOMATICALLY AND STORED
4

CONTINUED


THICKNESS
RANGE >.25"
ALUMINUM AND
ITS ALLOYS
STEEL AND
ITS ALLOYS
COPPER AND
ITS ALLOYS
ADVANCED
COMPOSITE
MATERIALS
SELECT 5 MHz, .5" DIA
TRANSDUCER FOR UP TO
30" IN MATERIAL
SELECT 2.25 MHz, .5" DIA
TRANSDUCER FOR UP TO 30"
IN MATERIAL
1 MHz, 1/2 INCH DIA
FOR UP TO 5-10 INCH
THICK MATERIAL
D
CONNECT THE APPROPRIATE
TRANSDUCER TO FLAW
DETECTOR BASED ON
MATERIAL AND THICK-
NESS RANGE
CHANGE
TRANSDUCER
OK
CHECK FOR
ACOUSTICAL ECHO
NOT PRESENT
CHECK FOR TRIGGER
AND OTHER SETTINGS
NOT-OK
CHANGE VARIOUS
SETTINGS
PRESENT
SELECT AND APPLY THE
PROPER COUPLANT IF
CONTACT MODE - D
SCAN THE DESIRED
REGION WITH
ULTRASONIC TRANS.
CHECK THE A/D CONVERTER
FOR ITS OPERATION AND
CALIBRATION
CHECK FOR
BWE
PRESENT
THICKNESS MEASUREMENT
IS CARRIED OUT AUTO-
-MATICALLY AND STORED
NOT PRESENT
DECREASE ATTENUATION
AND INCREASE ENERGY
CHECK FOR
BWE
PRESENT
D
NO-GO
NOT PRESENT
CHANGE TO A LOWER
FREQUENCY TRANSDUCER
GO
CHECK SURFACE
PARALLELISM

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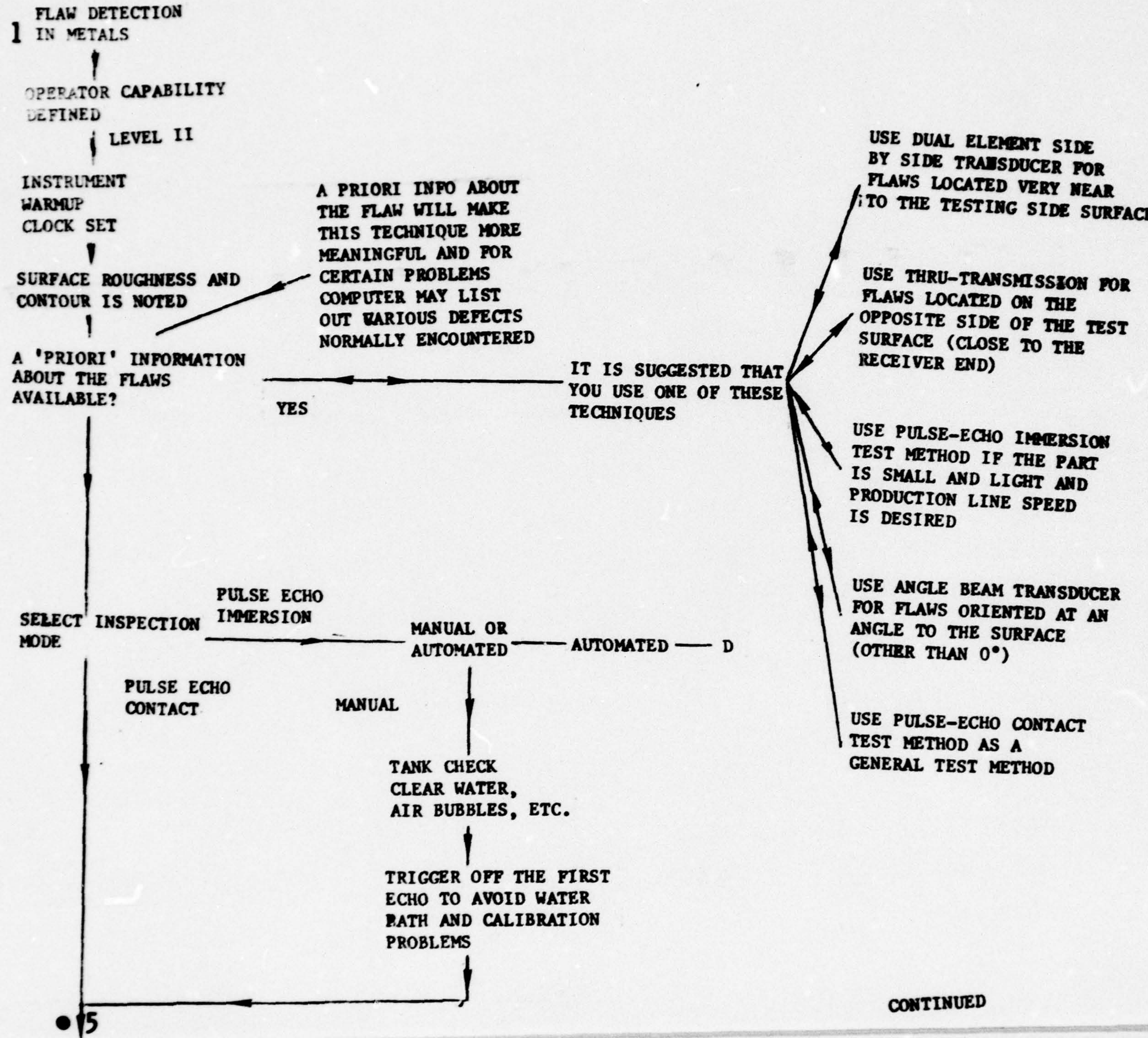
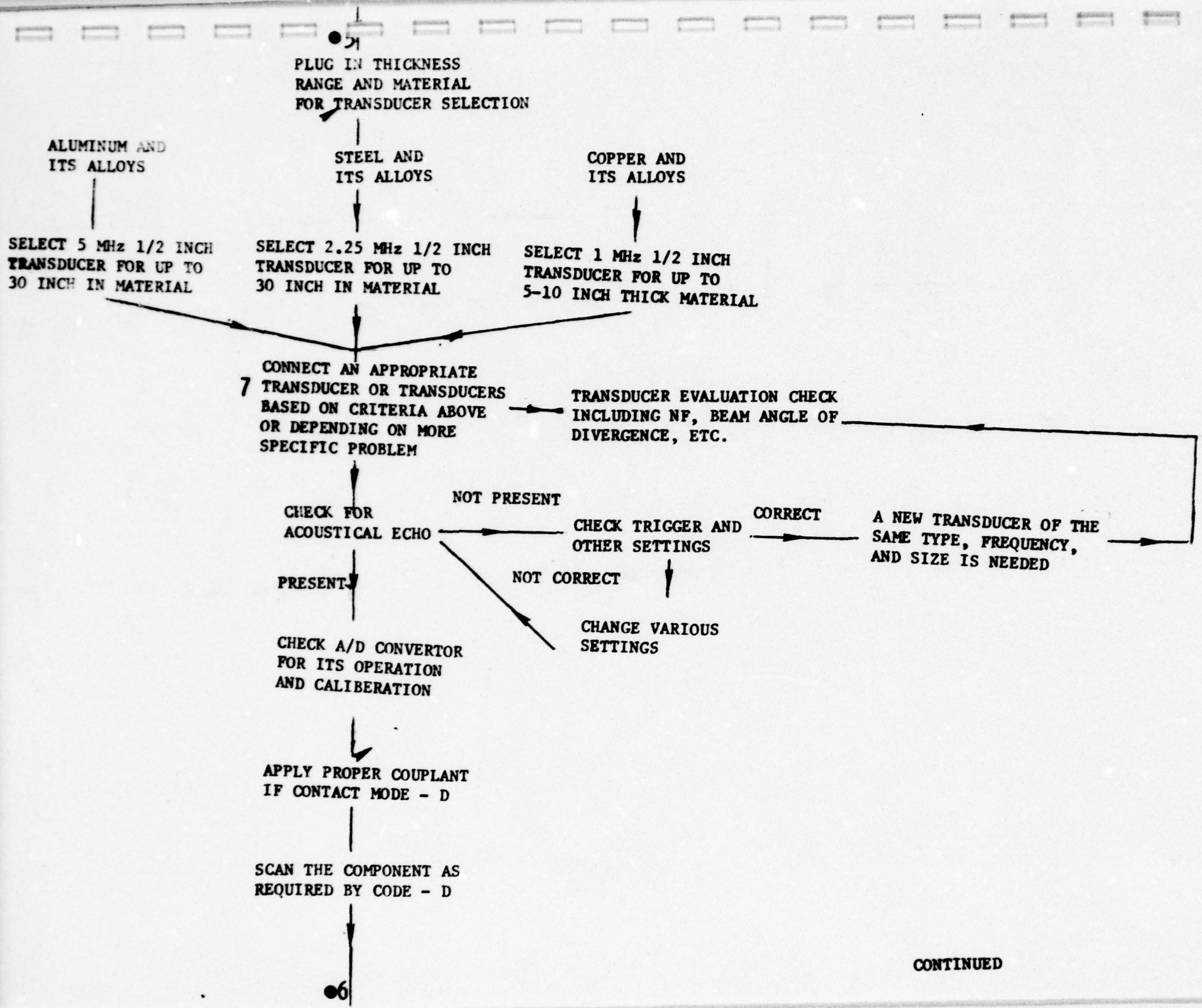
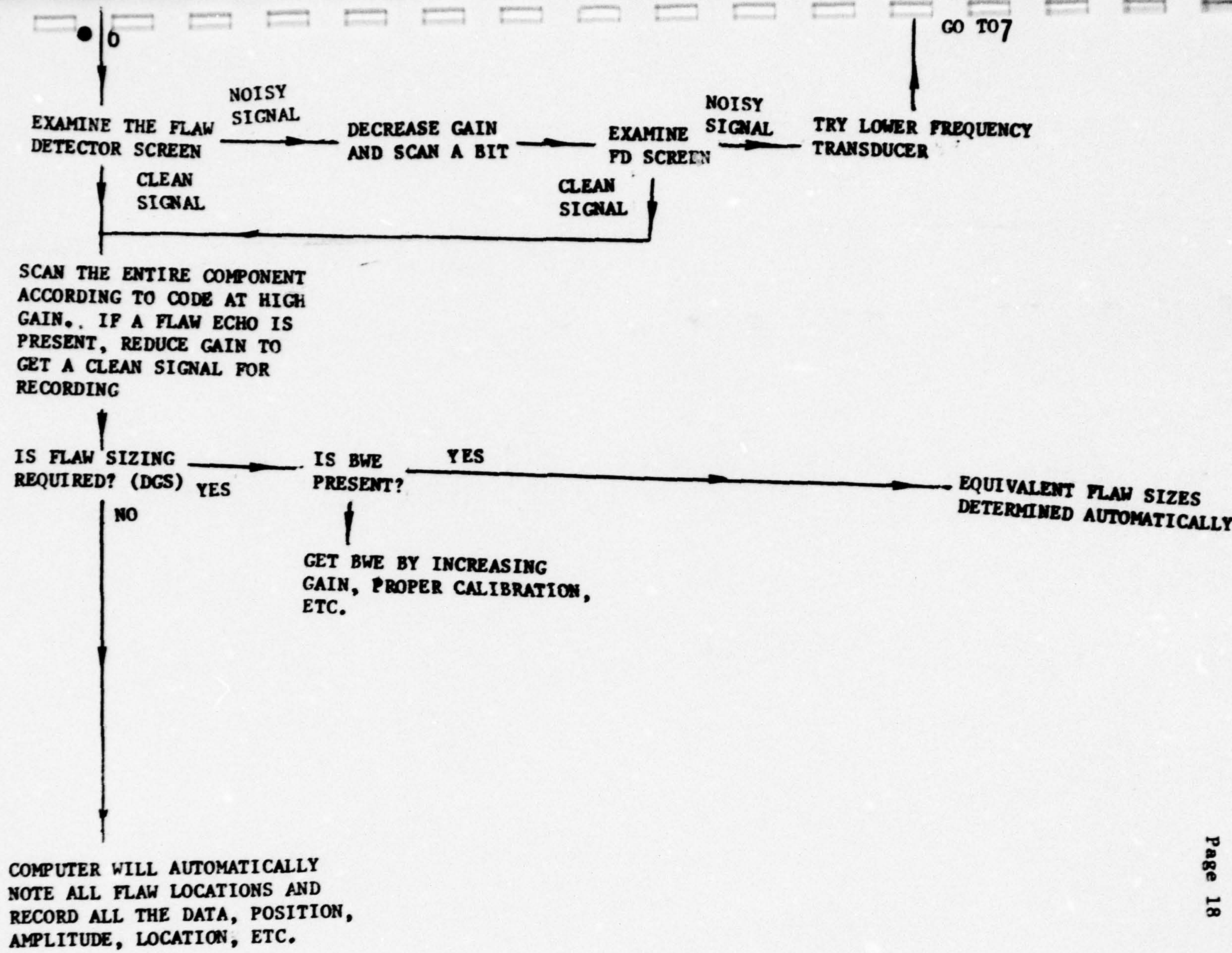

1
FLAW DETECTION IN METALS
OPERATOR CAPABILITY DEFINED
LEVEL II
INSTRUMENT WARMUP CLOCK SET
SURFACE ROUGHNESS AND CONTOUR IS NOTED
A PRIORI INFO ABOUT THE FLAW WILL MAKE THIS TECHNIQUE MORE MEANINGFUL AND FOR CERTAIN PROBLEMS COMPUTER MAY LIST OUT VARIOUS DEFECTS NORMALLY ENCOUNTERED
A 'PRIORI' INFORMATION ABOUT THE FLAWS AVAILABLE?
YES
IT IS SUGGESTED THAT YOU USE ONE OF THESE TECHNIQUES
USE DUAL ELEMENT SIDE BY SIDE TRANSDUCER FOR FLAWS LOCATED VERY NEAR TO THE TESTING SIDE SURFACE
USE THRU-TRANSMISSION FOR FLAWS LOCATED ON THE OPPOSITE SIDE OF THE TEST SURFACE (CLOSE TO THE RECEIVER END)
USE PULSE-ECHO IMMERSION TEST METHOD IF THE PART IS SMALL AND LIGHT AND PRODUCTION LINE SPEED IS DESIRED
USE ANGLE BEAM TRANSDUCER FOR FLAWS ORIENTED AT AN ANGLE TO THE SURFACE (OTHER THAN 0°)
USE PULSE-ECHO CONTACT TEST METHOD AS A GENERAL TEST METHOD
SELECT INSPECTION MODE
PULSE ECHO IMMERSION
MANUAL OR AUTOMATED
AUTOMATED
D
PULSE ECHO CONTACT
MANUAL
TANK CHECK CLEAR WATER, AIR BUBBLES, ETC.
TRIGGER OFF THE FIRST ECHO TO AVOID WATER BATH AND CALIBRATION PROBLEMS
5

CONTINUED


5
PLUG IN THICKNESS RANGE AND MATERIAL FOR TRANSDUCER SELECTION
ALUMINUM AND ITS ALLOYS
STEEL AND ITS ALLOYS
COPPER AND ITS ALLOYS
SELECT 5 MHz 1/2 INCH TRANSDUCER FOR UP TO 30 INCH IN MATERIAL
SELECT 2.25 MHz 1/2 INCH TRANSDUCER FOR UP TO 30 INCH IN MATERIAL
SELECT 1 MHz 1/2 INCH TRANSDUCER FOR UP TO 5-10 INCH THICK MATERIAL
7
CONNECT AN APPROPRIATE TRANSDUCER OR TRANSDUCERS BASED ON CRITERIA ABOVE OR DEPENDING ON MORE SPECIFIC PROBLEM
TRANSDUCER EVALUATION CHECK INCLUDING NF, BEAM ANGLE OF DIVERGENCE, ETC.
CHECK FOR ACOUSTICAL ECHO
NOT PRESENT
CHECK TRIGGER AND OTHER SETTINGS
CORRECT
A NEW TRANSDUCER OF THE SAME TYPE, FREQUENCY, AND SIZE IS NEEDED
NOT CORRECT
CHANGE VARIOUS SETTINGS
PRESENT
CHECK A/D CONVERTOR FOR ITS OPERATION AND CALIBERATION
APPLY PROPER COUPLANT IF CONTACT MODE - D
SCAN THE COMPONENT AS REQUIRED BY CODE - D
6

CONTINUED


0
EXAMINE THE FLAW DETECTOR SCREEN
NOISY SIGNAL
DECREASE GAIN AND SCAN A BIT
EXAMINE FD SCREEN
NOISY SIGNAL
TRY LOWER FREQUENCY TRANSDUCER
GO TO 7
CLEAN SIGNAL
CLEAN SIGNAL
SCAN THE ENTIRE COMPONENT ACCORDING TO CODE AT HIGH GAIN. IF A FLAW ECHO IS PRESENT, REDUCE GAIN TO GET A CLEAN SIGNAL FOR RECORDING
IS FLAW SIZING REQUIRED? (DGS)
YES
IS BWE PRESENT?
YES
EQUIVALENT FLAW SIZES DETERMINED AUTOMATICALLY
NO
GET BWE BY INCREASING GAIN, PROPER CALIBRATION, ETC.
COMPUTER WILL AUTOMATICALLY NOTE ALL FLAW LOCATIONS AND RECORD ALL THE DATA, POSITION, AMPLITUDE, LOCATION, ETC.

CONTINUED

2 FLAW CLASSIFICATION IN METALS

DEFINE NATURE OF CLASSIFICATION DESIRED

LOCATE ALL THE FLAWS USING FLAW DETECTION CHART AND NOTE THEIR POSITIONS

USE AUTOMATIC TRANSDUCER CHARACTERIZATION AND BEAM PROFILING OF THE TRANSDUCERS - D

FOR REPRODUCIBILITY USE EITHER GO - NO GO CRITERIA OR DECONVOLUTION ALGORITHM
D

USE FOCUSSED TRANSDUCER, LINEAR AND ANNULAR ARRAYS
D

COLLECT ADDITIONAL INFO ABOUT THE FLAW USING APPROPRIATE SEARCH UNITS AND COMPUTERIZED DATA ACQUISITION SYSTEM

USE SIGNAL PROCESSING ALGORITHMS.
HIGH SNR DESIRED FOR CLASSIFICATION

USE PATTERN RECOGNITION ALGORITHM DEVELOPED FOR A SPECIFIC PROBLEM e.g.

OTHER IMPORTANT NDT PROBLEMS - D

SMOOTH VS. SHARP FLAW PROBLEM

FATIGUE PROBLEM - D

BOND (ADHESIVE) PROBLEM

CRACK LENGTH PROBLEM - D

HARDWARE MICROPROCESSOR IMPLEMENTATION
(A SMALL MODUL FOR A SPECIFIC PROBLEM)
(MANY PRODUCTS TO BE DEVELOPED AT THIS STAGE)

APPENDIX A

Article 1. "ON SELECTED ASPECTS OF PHASE ANALYSIS IN ULTRASONIC TESTING" Joseph L. Rose and Gurvinder Pal Singh, presented at the 11th Symposium on Nondestructive Evaluation, April 20-22, 1977 at San Antonio, Texas.

ON SELECTED ASPECTS OF PHASE ANALYSIS IN ULTRASONIC TESTING

Joseph L. Rose and Gurvinder Pal Singh
Drexel University
Philadelphia, Pennsylvania

Abstract

Selected aspects of Fourier transform phase analysis associated with ultrasonic inspection are reviewed in this paper. Phase signature techniques that may be useful in flaw characterization and classification work are covered. Mathematical details of the deconvolution processes are presented with emphasis on transducer compensation software and extensions to pattern recognition and learning machine analysis. In particular, four topics are discussed: shifting characteristics, deconvolution, phase signature techniques, and value of phase in learning machine analysis. In summary, fundamental concepts in phase analysis are studied that will enable researchers to advance the state-of-the-art in ultrasonic inspection, signal analysis, and instrumentation design and selection.

A. INTRODUCTION

Until recently, ultrasonics has been used as an effective nondestructive flaw detection tool. It could be used quite readily to locate flaws in homogeneous isotropic materials. But with the advent of composite materials, bonded materials, the tremendous increase in the complexity of structural designs, and the conservation of material and fuel, mere flaw detection is no longer sufficient. In fact, it is becoming increasingly difficult to define "flaw". This is also contributed to the electronics and instrumentation technological advances. The question now becomes "Is this flaw detrimental to the effectiveness of the structure?" Before this question can be answered, however, it is necessary to determine as many characteristics of the flaw as possible for failure analysis.

"Ultrasonic Spectroscopy", a name given by Gericke [1], has been used to obtain more information about flaws. Additional details on spectral analysis can be found in [2,3,4]. It has also been used to study transducer waveforms, measure thickness of thin materials, measure bond strength, inspect composite materials and to study attenuation and microstructure in a material. Work to date has relied quite heavily on amplitude versus frequency analysis, with little attention placed on the values of phase analysis. The purpose of this paper is to outline selected aspects of phase analysis that might be useful in advancing the state-of-the-art in ultrasonic testing. Four selected topics in phase analysis are, therefore, included below.

Before solving a particular problem, it is necessary to understand the phase profile characteristics.

$f(t) \rightarrow$ time domain representation of an ultrasonic signal

$F(\omega) \rightarrow$ frequency of an ultrasonic signal

$$F(\omega) = |F(\omega)|\, e^{j\phi(\omega)} = R(\omega) + jI(\omega)$$

$$\phi(\omega) = \tan^{-1}\left\{+\frac{I(\omega)}{R(\omega)}\right\}$$

$\phi(\omega) \rightarrow$ Phase Angle

B. DISCUSSION

1. Time Shifting Characteristics

The subject of the time shifting characteristic associated with the pulse location within an electronic gate and its affect on phase angle is reviewed in this section. Although details of the procedure are straight forward from a mathematical point of view, they are included here for reference purposes to remind that the

characteristic is important and to provide a guideline for coping with this shift.

Let $f(t)$ represent the ultrasonic pulse shape in the time domain and $F(\omega)$ its Fourier transform. Let $f(t)$ be shifted by a time constant ζ so that $f(t-\zeta) = g(t)$. The function $g(t)$ transforms to $G(\omega) = F(\omega)\, e^{-j\omega\zeta}$ in accordance with the Fourier transform property. Again,

$$
\begin{aligned}
G(\omega) &= F(\omega)^{-j\omega\zeta} \\
&= F(\omega)\left[\mathrm{Cos}(\omega\zeta) - j\ \mathrm{Sin}(\omega\zeta)\right]
\end{aligned}
$$

$$
\begin{aligned}
|G(\omega)| &= \left[|F(\omega)|^2\{\mathrm{Cos}^2(\omega\zeta)\} + |F(\omega)|^2\{\mathrm{Sin}^2(\omega\zeta)\}\right]^{\frac{1}{2}} \\
&= |F(\omega)|\ \left[\mathrm{Cos}^2(\omega\zeta) + \mathrm{Sin}^2(\omega\zeta)\right]^{\frac{1}{2}} \\
&= |F(\omega)| \qquad (1)
\end{aligned}
$$

which demonstrates that the pulse shift does not alter the magnitude of the Fourier transform. Time shifting, however, results in a change in the phase angle as shown below

$$F(\omega) = |F(\omega)|\ e^{j\phi(\omega)}$$

whereas time shifted pulse results in

$$G(\omega) = F(\omega)\ e^{-j\omega\zeta}$$

or

$$
\begin{aligned}
G(\omega) &= |F(\omega)|\ e^{+j\phi(\omega)}\ e^{-j\omega\zeta} \\
&= |F(\omega)|\ e^{j(\phi(\omega) - \omega\zeta)} \qquad (2)
\end{aligned}
$$

Also

$$G(\omega) = |G(\omega)|\ e^{j\phi(\omega)} \qquad (3)$$

Combining (2) and (3), we get

$$|G(\omega)|\ e^{j\phi(\omega)} = |F(\omega)|\ e^{j(\phi(\omega) - \omega\zeta)}$$

from equation (1)

$$|G(\omega)| = |F(\omega)|$$

$$\phi(\omega) = \phi(\omega) - \omega\zeta \pm 2k\pi$$

where k is an integer and introduced due to the periodicity of the function.
Hence the new phase angle due to pulse shift is given by the old phase angle minus $\omega\zeta$ if the pulse is moved to right (away from origin). Similarly, if the pulse is moved to the left-hand side inside the gate (towards the origin), new phase angle is given by

$$\phi(\omega) = \phi(\omega) + \omega\zeta \pm 2k\pi$$

In other words,

$$\phi_{new} = \phi_{old} \pm \omega\zeta \pm 2k\pi$$

or more appropriately

$$\omega\zeta = \phi_{new} - \phi_{old} \mp 2k\pi$$

where the sign depends upon the new location of the pulse as compared to the old one.

A computer program using the fast Fourier transform was used to analyze the gated pulse in the time domain to obtain the Fourier spectrum and phase angle vs. frequency data. Variations of phase angles due to movement of the pulse within the gate were studied. It was observed that two conditions must be satisfied in order to attain the above results. They are, namely,

(i) band width = 2 x center frequency,

and

(ii) that the shifted (new) pulse lies on the same side of $\frac{gate}{2}$ as the old one. Satisfaction of the above two conditions arises, naturally, if one considers the discrete Fourier transform [5]. Sample results are illustrated in Fig. 1.

It might be pointed out that phase profiles that are nonlinear could come about as a result of examining the results from multiple flaw situations. Additional work is currently being undertaken on this project to combine both theoretical and experimental aspects.

2. Deconvolution

The subject of transducer compensation is tremendously critical in many problems of ultrasonic inspection. It would be desirable to compare output on a given day with a particular instrument and operator with results obtained from some earlier data acquisition period. A basic deconvolution model is outlined in this paper that contains some hope for solving this difficult transducer compensation problem. It might be pointed out that results to date do not provide us with a complete solution to the problem because of the nonlinearities inherent in an ultrasonic system as well as the available ultrasonic input pulses that must be used. The future, however, shows promise for a transducer compensation algorithm and deconvolution provided this mathematical process is coupled with an acceptance criteria of an ultrasonic transducer. A "go" "no go" acceptance criteria on certain signal features, as an example, center frequency, 6dB down band width, pulse duration, and so on, must be developed.

A simple deconvolution model is presented in Fig. 2. For a linear system

$$f(t) * g(t) = h(t)$$

where * indicates convoluted with

or

$$h(t) = \int_{-\infty}^{\infty} f(t)\ g(t-\zeta)\ d\zeta$$

The evaluation of this integral can be carried out in a computationally efficient fashion in frequency domain since convolution in time domain is multiplication in frequency domain. For example:

$$f(t) * g(t) = h(t)$$

$$\text{or} \quad F(f)\,G(f) = H(f)$$

$$\text{or} \quad G(f) = \frac{H(f)}{F(f)}$$

$$\text{or} \quad G(t) = F^{-1}\left\{\frac{H(f)}{F(f)}\right\}$$

Theoretically, therefore, deconvolution procedure can be used to provide the transfer function of the system.

A more realistic model similar to that presented in [6] for ultrasonic inspection is as shown in Fig. 3.

$$O(t)=g(t)*p(t)*c(t)*m(t)*f(t)*m(t)*c(t)*p(t)$$

Fourier transform of the above yields

$$O(f) = F(f)\,A(f)$$

where

$$A(f)=G(f)\,P^2(f)\,M^2(f)\,C^2(f)$$

$$F(f) = \frac{O(f)}{A(f)}$$

Since A(f) is in the denominator, any low amplitude frequency component in the reference signal will result in a considerably noisy output. The use of windowing functions [7] (triangular, Hanning, Hamming) is necessary in order to cut out very low and very high frequency component. F(f) is obtained by point by point devision of the two signals multiplied with a windowing function and then inverse Fourier transformed to time domain. It is important to point out that the correct phase angle be used while performing the inverse Fourier transform. Time domain representation so obtained yields the transfer function or the reflectivity function for the flaw.

Implementation of this deconvolution technique is tedious and the results obtained are not as accurate as desired due to the nonlinearities present in the ultrasonic test system. Additional work on this subject, coupled with a suitable transducer acceptance criteria will be carried out shortly to advance the state of the art on this subject.

3. Phase Signature Techniques

Rose and Schlemm [8] conducted a theoretical study on single, dual and triple cylindrical porosity cluster model to obtain more insight into the values of the phase angle profile. Their study indicated that the phase signature revealed some details that could be used to characterize the flaw. Rose, Mast and Walker [9] observed that the phase profile slope will vary for various flaw cluster situations and, therefore, can be used for determining flaw type, i.e., cluster, porosity, etc. They also utilized phase signatures to identify disks from spheres and were able to do so in all the cases studied. Rose, Mast and Niklas [10] also present a sample problem for thickness measurement utilizing phase angle.

Johnson [11] has indicated that the phase information may prove valuable in identifying a particular type of surface geometry.

Phase signature techniques may prove useful in transducer characterization and also in pattern recognition work presented in the next section.

4. Value of Phase in Learning Machine Analysis

The flaw sorting study was carried out recently by Rose [12] that served as a feasibility study in the sorting of 23 selected flaws by techniques of pattern recognition. Overall index of performance for that particular study turned out to be 92% in differentiating sharp vs. smooth edge defect. The type of flaws considered in the study are illustrated for reference purposes in Table I and II. The flaw sorting study was most difficult in separating singular and multiple smooth type situations. In particular, type 3, 9, and 10 were difficult to separate from each other and in many cases 9 and 10 appeared as though they were sharp edged defects because of the superposition affect occurring from the scattered energy at the angle beam transducer. Index of performance values in separating the smooth edge defects was very poor. It was, therefore, decided to incorporate some phase analysis features that might be useful in improving the index of performance in this classification problem. First attempts were made at examining phase profiles from the angle beam scattered data in two parts, one from the longitudinal component of the signal and the other from shear component of the ultrasonic signal. Data acquisition technique is illustrated in Fig. 4. Visual observation of the phase profile proved tedious and not immediately beneficial. More advanced work in pattern recognition, however, in using computerized feature extraction and data analysis might prove worthwhile. It was decided though to use normal beam transducer to get some idea if the phase profile could be used in this case. Keeping in mind that the angle beam approach was used to look at longitudinal and shear component coming from the mode conversion occurring at the flaw in question, physics dictates that a normal beam transducer might be suitable for flaw type determination, in particular, when examining the phase profile. Sample results of the normal beam data

acquisition technique are shown in Fig. 5.

Flaw multiplicity can be easily determined by counting the number of discontinuities in phase profile over an active frequency range. It might be pointed out that a careful examination of slope changes in frequency amplitude profile could reveal the identical information but observation of slope changes is much more difficult when compared to the large discontinuities that occur in the phase profile in Fig. 6.

Additional work calling for completely automated computerized feature extraction and then incorporation into the various techniques in pattern recognition described by Rose, namely, that of the nearest neighbor rule concept, the Fischer linear discriminant function and application of adaptive learning network will certainly be worthwhile if indeed this theoretical approach becomes a practical approach to solving problems in flaw classification. Certainly the results presented here appear promising but algorithms combining fuzzy logic technique with the advanced concepts of pattern recognition are definitely required along with a suitable transducer acceptance criteria on whether the phase data should be included in the analysis or not.

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TABLE 1 – Electro-Discharge Machined Side Drilled Flaw Types

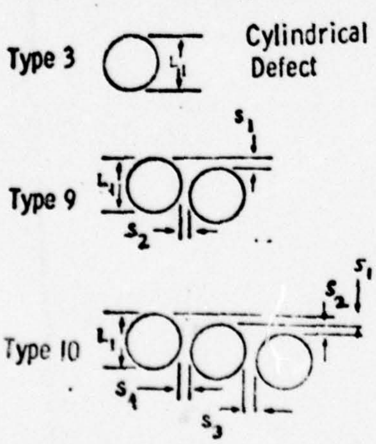
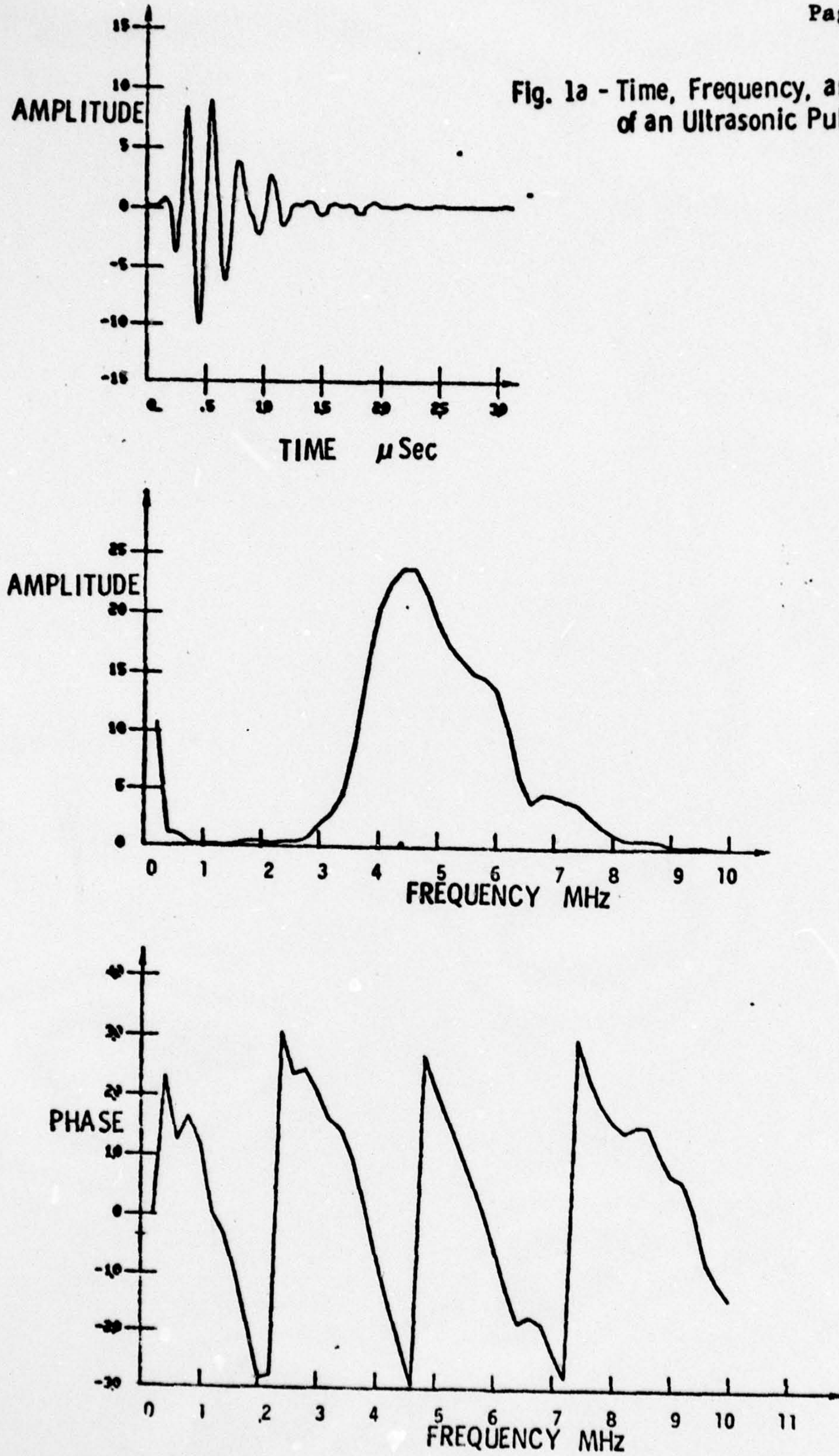


TABLE 2–Test Specimen Flaw Characteristics

Type	L_1 (mm)	S_1 (mm)	S_2 (mm)	S_3 (mm)	S_4 (mm)
3	4.76	-	-	-	-
3	3.18	-	-	-	-
3	1.59	-	-	-	-
9	3.18	1.59	1.59	-	-
9	3.18	0.58	0.58	-	-
9	3.18	0.58	1.17	-	-
10	3.18	0.58	0.58	0.58	0.58
10	3.18	0.58	0.58	0.58	1.17

Fig. 1a - Time, Frequency, and Phase Profile of an Ultrasonic Pulse (time shift ζ = 0)



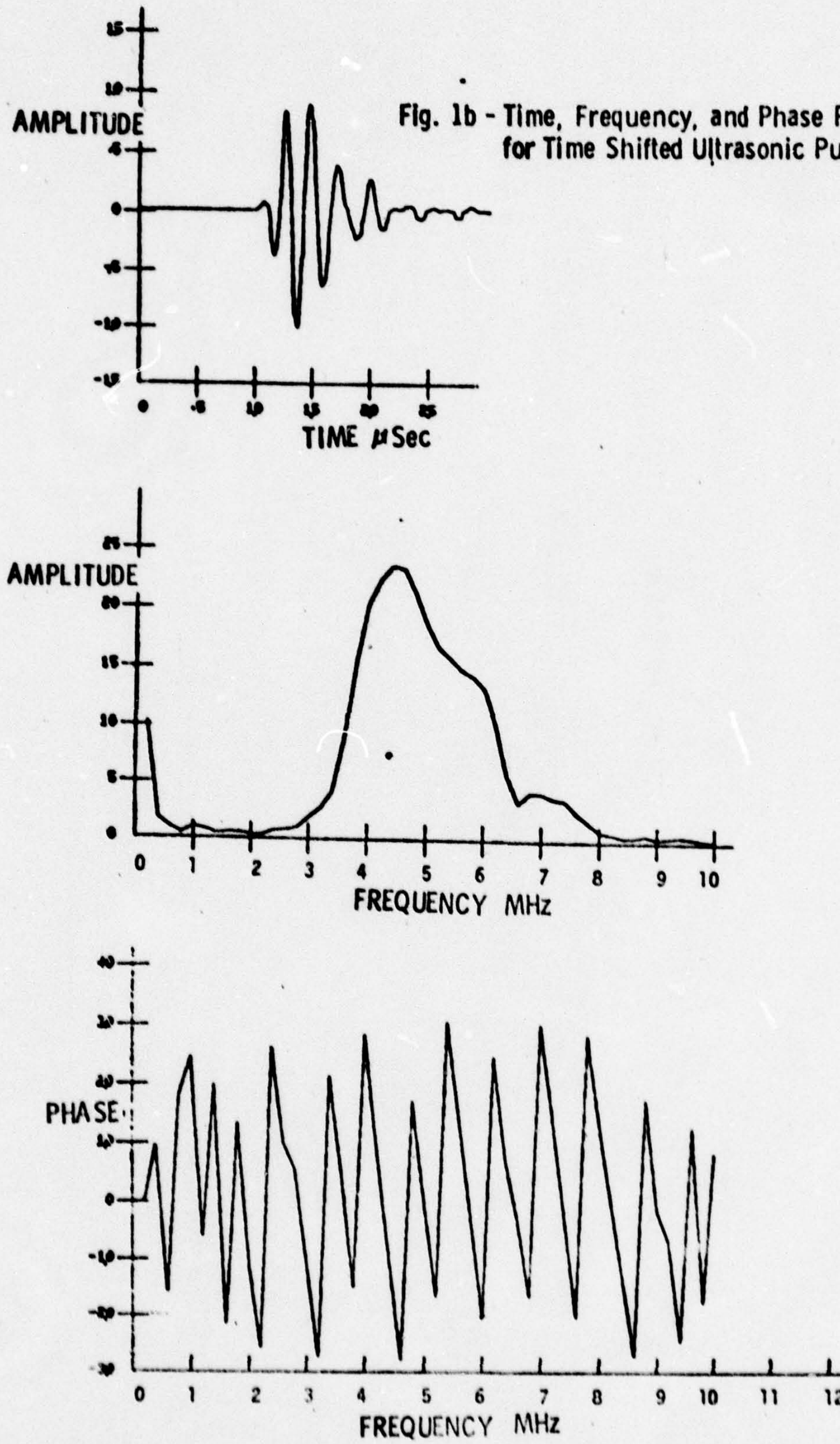


Fig. 1b - Time, Frequency, and Phase Profile for Time Shifted Ultrasonic Pulse (ζ = 1.00 μ sec.)

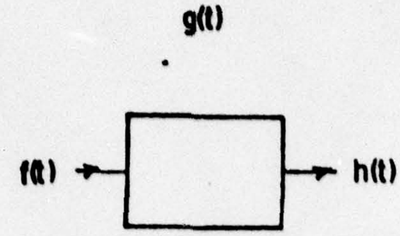


Fig. 2 - A Basic Deconvolution Model

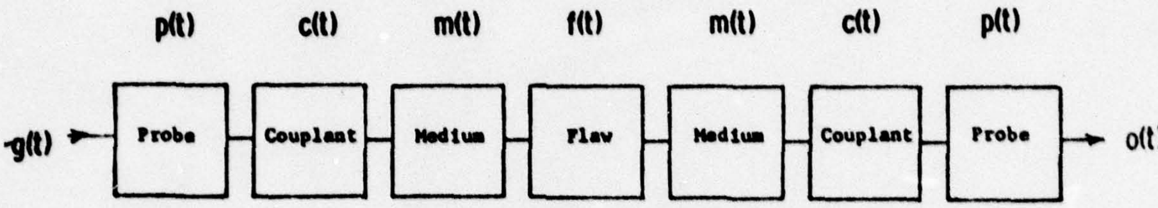


Fig. 3 - A Model for Ultrasonic Test System

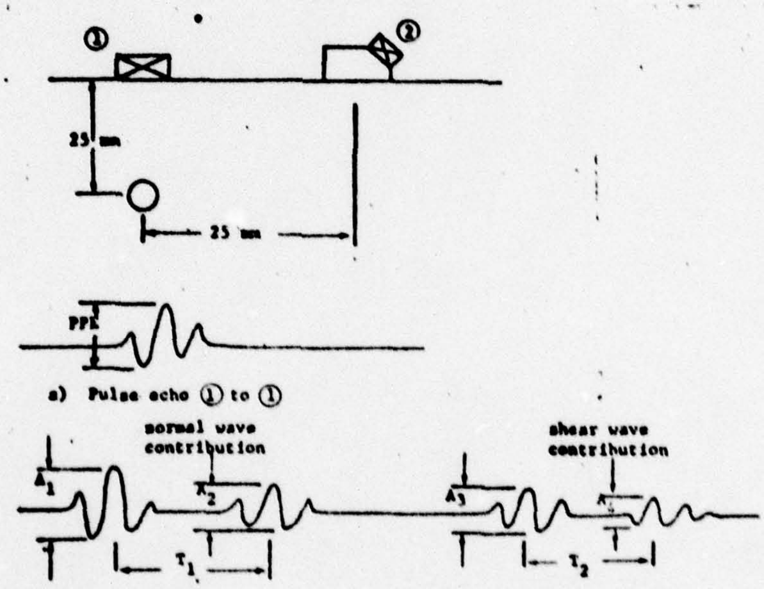


Fig. 4 - Data Acquisition Technique

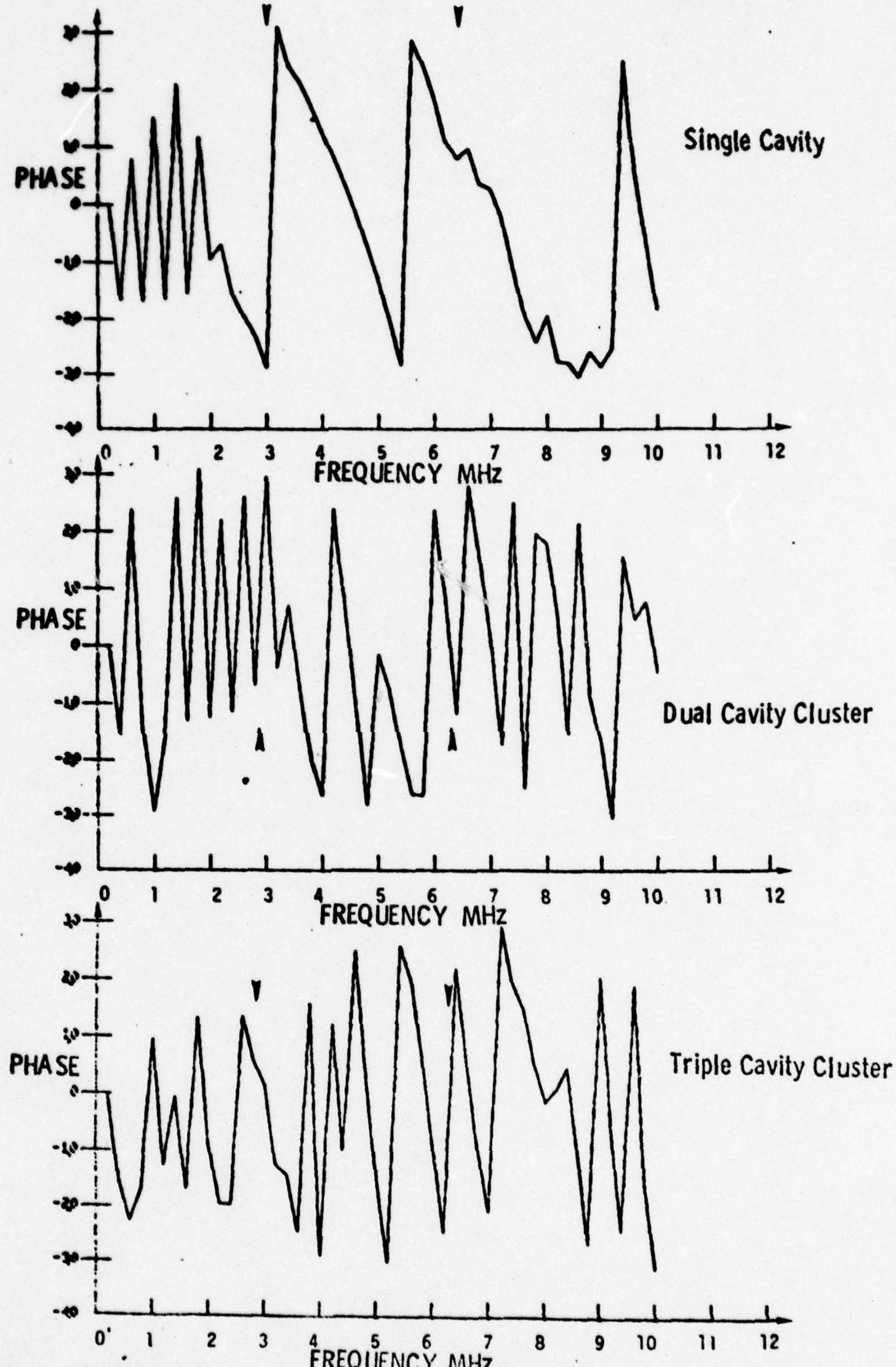


Fig.5 - Demonstration of Phase Profile Potential for Flaw Classification

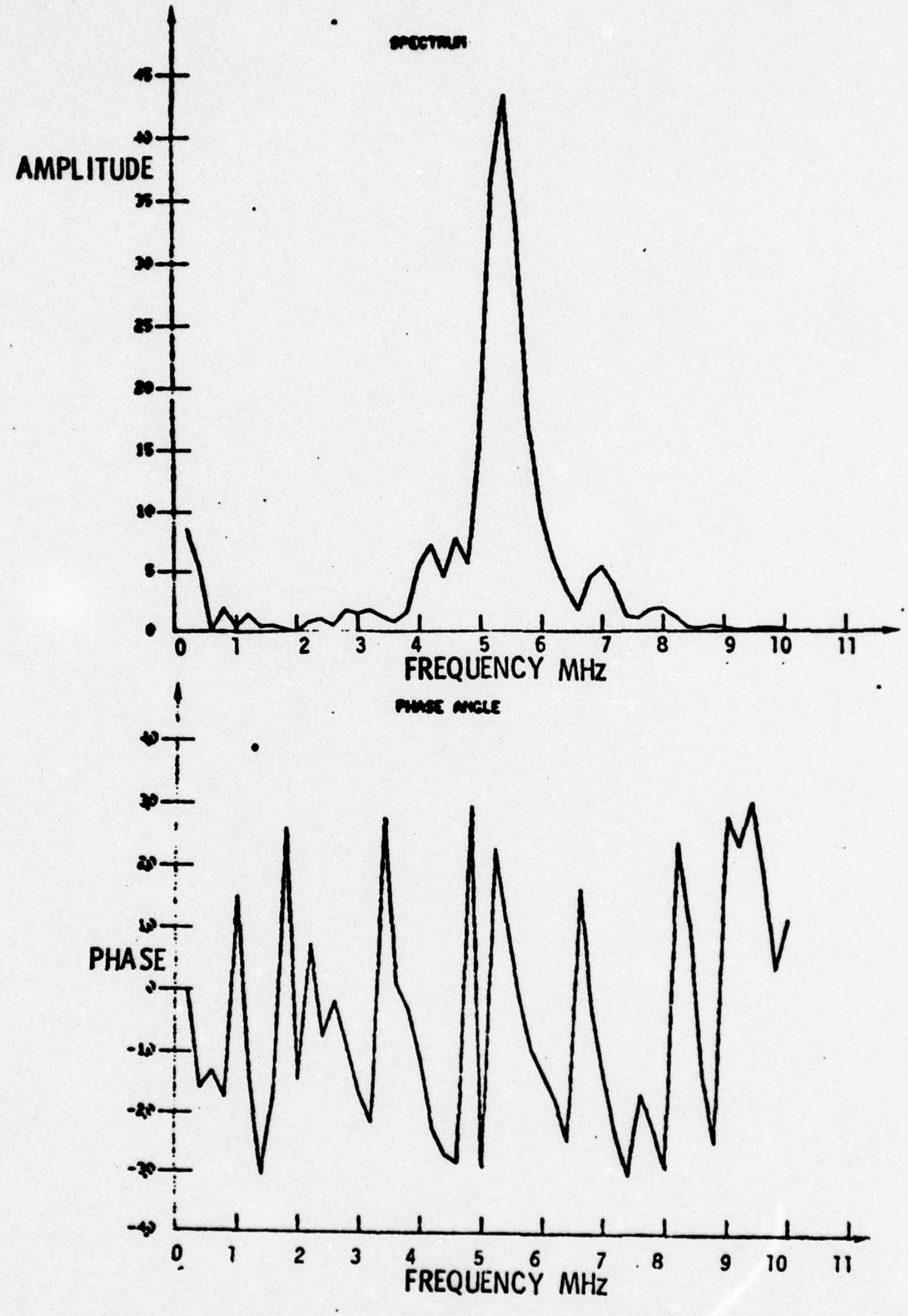


Fig. 6 - Comparison of a Typical Frequency and Phase Profile

APPENDIX B

Article 1. "Transducer Compensation Concepts in Flaw Classification" Joseph L. Rose and Michael J. Avioli, presented at the ASNT Spring Conference, April 2-7, 1978 at New Orleans, Louisiana.

"Transducer Compensation Concepts in Flaw Classification"

by

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Abstract

Flaw classification analysis is quite often strongly influenced by the type of ultrasonic waveform that is generated by an ultrasonic transducer. One goal of this paper is to introduce procedures that could possibly make flaw classification algorithms become somewhat independent of certain ultrasonic waveform characteristics being used in the data acquisition procedure. Data acquisition of ultrasonic pulse echo signals depends quite strongly on many test system characteristics, in particular, special characteristics of the ultrasonic transducer and pulser-receiver instrument characteristics. A transducer compensation procedure is presented in this work that requires a suitable reference signal containing "noise" contributed only by system components external to the unknown flaw, and in software, a processing scheme is designed to remove external effects, therefore, allowing concentration on flaw characteristics contained within the ultrasonic signal.

The processing scheme has four general components: Acceptor, Compensator, Comparator, and Evaluator. The acceptor is basically a gate that decides whether or not a particular transducer is usable for the problem at hand. The compensator implements a mathematical deconvolution process. The comparator does a feature by feature similarity check on the desired signal and the compensated signal. The evaluator is any scheme that can determine the performance of a given transducer. In particular, the al-

gorithm under study may be used to evaluate transducer performance. The evaluation stage is followed by an examination of the comparator results. Tolerances relating to the acceptability of a transducer are obtained through this final stage.

Model analysis is used to study the compensation problem. A Layered Model is used with various levels of system "noise" being introduced, in order to examine the "noise" effects in the deconvolution computation process. Promise for attaining success in this difficult compensation problem is good, particularly when considering signal averaging as a signal processing tool.

INTRODUCTION

The subject of reliability in ultrasonic examination is tremendously important. Higher reliability values have been associated with sample problems in ultrasonic inspection, for example, in thickness measurement and in reflector location analysis. The subject of flaw classification, on the other hand, usually based on various features of pulse shape have created various problems in classification reliability. Errors in many cases have been attributed to many different transducer pulse form variations, coming about because of such instrumentation changes as pulser, receiver, and gain settings. Cable influences have produced changes in pulse shape. In fact, pulse shape variations have been reported for the same transducer on different days and at different times because of both environmental and other unknown changes in the ultrasonic instrumentation network. The goal of this paper is to tackle the problem of improved reliability by way of establishing a suitable transducer compensation system to account for the changes in ultrasonic pulse shape for one reason or another.

Once guidelines for transducer compensation are established, work on the establishment of high reliability flaw classification algorithms can be carried out as a function of a single transducer pulse shape. The numerous variations of transducer pulse shape need not be considered in the already difficult algorithm development program for flaw and material variation. Variations in pulse shape will, therefore, be accounted for by employing a transducer compensation routine. Obviously, transducer compensation will not always be possible. A transducer acceptance criteria and compensation network is, therefore, proposed in this paper that will advance the state of the art in many ultrasonic inspection programs associated with advanced work in pattern recognition and computer learning analysis for flaw classification.

Reflector geometry analysis is strongly influenced by the type of ultrasonic waveform that is generated by an ultrasonic transducer. One goal of this paper is to introduce procedures that could possibly make flaw classification algorithms become somewhat independent of the ultrasonic waveforms used in data acquisition procedures. Acquisition of ultrasonic pulse data depends strongly on many test system characteristics, in particular, those of the ultrasonic transducer and pulser-receiver instrument.

Frederick and Seydel [1] have discussed a computer-based data processing system and compensation technique to increase the effective bandwidth of an ultrasonic transducer. Their study included the use of a reference function that aided in the preservation of phase information and the means for a point by point complex division. This technique improved axial resolution, but was not applied to transducer compensation analysis. Mucciardi [2, 3] used deconvolution (transducer compensation) as a preprocessing technique in his pattern recognition studies. This work presents a transducer compensation procedure that uses a concept of a transfer function [4] and a method of complex division that rely on suitable reference signals containing abberrations contributed only by system components external to the flaw system. This procedure, therefore, allows concentration on flaw characteristics contained within the ultrasonic signal.

Limited success in utilization of this compensation technique ~~was~~ demonstrated; the inverted amplitude-time profile being very noisy. Model analysis is used in this paper to study the compensation problem. This approach simplifies the generation of the data sets the analyst must use; whereas the complete and varied data set generation would be virtually impossible for the experimentalist, because of the unavailability of a significant number of flaw specimens required in the compensation and pattern recognition studies. A layered model is used with the various levels of

system "noise" being introduced in order to examine the "noise" effects in the deconvolution computation process. Promise for attaining success in this difficult compensation problem is good, particularly when considering signal averaging as a signal processing tool.

Theoretical Approach

a) Basic Concepts

Transducer compensation is essentially the removal of the effects of different transducers from a given test situation. Consider the procedure for determining the shape of a subsurface flaw by ultrasonic methods. Physically, a transducer is excited by a voltage spike ($G(\omega)$ $P(\omega)$), which distorts the crystal in the transducer ($T_1(\omega)$). This distortion is propagated as a pressure wave through the medium hosting the flaw. Upon incidence on the flaw, the wave is reflected distorting the transducer's crystal ($T_2(\omega)$), which generates a time-varying voltage. This voltage-time profile is amplified and is either displayed on a CRT, digitized and stored, or both.

The host medium, the flaw, and couplant may be viewed as a physical system excited by the initial distortion of the transducer crystal and responding with another distortion of the crystal. When transducers are changed, crystals are changed, and therefore excitaitons and responses from the same physical system are changed.

The linear systems approach to this problem is to consider the responses of the flaw system as the convolution of the excitation and impulse response of the system. Note that it is necessary to assume that <u>on receive</u> the transducer is linear. This is not unreasonable since signal levels are quite small on receive.

Mathematically,

$$\int_{-\infty}^{\infty} f(t)\, g(\tau - t)\, dt \rightarrow F(\omega) \cdot G(\omega)$$

where $F(\omega)$ = Fourier Transform of $f(t)$

$G(\omega)$ = Fourier Transform of $G(t)$

The system diagram for the above situation appears in Fig. 1a.

$$I_i(\omega) \cdot S(\omega) = O_i(\omega)$$

where $I_i(\omega)$ = Fourier Transform of input i

$O_i(\omega)$ = Fourier Transform of output i

$S(\omega)$ = Fourier Transform of Couplant, Medium and Flaw (known as the system transfer function)

This model admits a different definition of transducer compensation. Transducer compensation is the determination of the system transfer function (which is considered fixed).

Frequency domain analysis shows that for two different transducers, the following

$$I_1 \cdot S = O_1 \qquad S = \frac{O_1}{I_1}$$

$$I_2 \cdot S = O_2 \qquad S = \frac{O_2}{I_2}$$

Implying that the system transfer function is independent of transducer.

b) Deconvolution

Deconvolution is the process by which the transfer function of a physical system is determined. Analytically, this is a point by point division in the frequency domain, O/I.

The output O is usually taken as the return echo from the test piece. The input is determined by looking at the return echo from the back wall of a test block made of the same material as the system under test.

The Fourier Transforms of O and I are taken and complex division implemented. The result of this division is the system transfer function.

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Generalized Transducer Compensation

Pattern recognition algorithms should be designed with respect to a single well characterized transducer during the algorithm development stage. Practicality, however, requires that existing algorithms be able to handle inputs from a various assortment of transducers. The algorithm development process is a long and tedious task. One approach is to employ the so-called "shot gun" method. This method involves obtaining data from a multitude of transducers and designing an algorithm, that in some average sense, performs well for this collection of transducers. Unfortunately, a "typical" set of transducers does not exist.

The alternative to the "shot gun" approach is to implement a preprocessing routine that would modify the outputs of a set of transducers that have passed an acceptance criteria to "look" like they came from the algorithm design transducer. Figure 2 shows in flow chart form, the general concept of compensation. Here it is assumed that a particular transducer, in this instance, transducer K, was used to develop an algorithm with high reliability of performance. Transducers labeled 1 through N (excluding K) are first evaluated on a go no-go basis by an acceptance criteria. Those surviving this test are then used to probe the flaw and material system. Each transducer will produce a different output. These outputs are entered into a "transducer compensation" routine in order to simulate the output K (input to the algorithm). Not all transducers will be amenable to this operation. The body of this paper will demonstrate that bandwidth and noise characteristics are critical.

Acceptor Design Concept

Techniques for designing the logic associated with the development of an acceptor that would be useful in pattern recognition analysis are outlined in this section. It is proposed to make use of the theoretical deconvolution routine presented in this paper to establish guidelines for the acceptor design which essentially just provides us with a go no-go criteria for a new transducer. Let us consider a modified diagram of the generalized transducer compensation concept that was presented earlier. See Figure 3. Design input for the acceptor will come about by examining the output functions after deconvolution or by examining index of performance for a set of data after passing through the high reliability algorithm. In either case, experience based on both theoretical and experimental analysis will be used to establish an acceptance criteria for a given transducer. It is essential in this approach that a well characterized transducer be used with a list of characteristic features. Rather than carry out a detailed study of a fairly large number of transducers, it is proposed to consider theoretical variations on the transducer pulse form from which the high reliability algorithm was designed. The acceptor design will depend significantly on the system "noise". A procedure is proposed in this paper that combines various samples of system "noise" with the different input functions in an attempt to establish guidelines on transducer pulse forms that would obtain reasonable output results by way of the deconvolution routine. Acceptor design can, therefore, be based on a theoretical transfer function with the system "noise" providing us with the major errors or acceptance limits in the deconvolution process. Note that a noise free system indicates that all transducers are acceptable since the deconvolution process always performs satisfactorily in this linear systems approach.

Theoretical Deconvolution Sample Problems

The general scheme employed in the following example is shown in Figure 4. The elements labeled "noise" are all distinct from each other and for this study had three possible states: no noise, one shot noise, and noise averaged thirty-two times. The summing junctions represent the fact that additive noise was assumed in these examples.

Realistic input ultrasonic waveforms were selected for this study. A Layered Media Transfer function was taken form a closed form solution in Brekhovskikh[5] as outlined in Table I and illustrated in Fig. 9a. Two different ultrasonic waveforms were selected as input to the three layered structure. The input function characteristics are summarized in Table II and shown in Figures 5a, 5b, 6a, and 6b. Output functions utilizing the layered media transfer function are presented in Figures 7a, 7b, 8a, and 8b. The transfer function for these functions was calculated with the deconvolution calculation process.

$$TF_1 = \frac{O_1}{I_1}$$

$$TF_2 = \frac{O_2}{I_2}$$

These functions are shown in Figures 9b and 9c. The echoes were obtained by first calculating TF_1 and TF_2 and then multiplying the Fourier Transforms of input one and input two by TF_1 and TF_2 respectively, and finally inverting the products.

It was noticed that the transfer functions obtained by deconvolution were somewhat distorted and shifted to the left. This is attributed to division algorithm noise (see Appendix I). The waveforms obtained through inversion were not distorted and were essentially as in Figures 5c and 6c. It would seem that once the transfer function of the system was obtained, there would be no need to calculate the time domain echo. Many ultrasonic

tests, however, are based on such parameters as peak-to-peak value, pulse duration, fall times (decay) and so forth. These values are not readily available from the transfer function, although studies may be made to deduce the relations between certain useful parameters and their manifestation in the transfer function. Therefore, in order to present results in a format convenient to both the mathematician and engineer, ampltude versus time analysis is covered along with the more basic transfer function.

Deconvolution with System "Noise"

System "noise" was added to the theoretical results presented in Figures 5a and 6a. A different set of "noise" was added to each signal, a sample of which is shown in Figures 10a and 10b. "Noise" was produced from fast data acquisition consisting of UTA2 pulser-receiver unit, stepless gate, and Biomation 8100 A/D converter, as data was transferrred into a PDP 11/05 minicomputer. The goal of this study was to evaluate the "noise" influences on the deconvolution process. First of all, let's consider the process of making the output function number 2 look like output function number 1.

$$O_2' = \frac{I_1 O_2}{I_2}$$

This result is shown in Figures 11c and 12a. The result is quite noisy, but it is obvious that the result resembles the ideal function O_1, shown in Fig. 7.

The reverse computation for O_1' is shown in Figures 11b and 12b.

$$O_1' = \frac{I_2 O_1}{I_1}$$

This result resembles the ideal result shown in Fig. 8.

It should be noted that the result O_1' is substantially "cleaner" than result O_2'. This is the effect of bandwidth. The O_2/I_2 complex division was essentially "narrow band", while the O_1/I_1 division was essentially "broad band".

The inverse of the power spectrum of a pulse basically looks like a parabola. In the frequency domain, this means low and high frequencies are accented. The broader or wider the "parabola", the lesser the effect on the low and high frequency portions of the transfer function.

Figure 13 gives a pictorial representation of the complex division process. Complex numbers may be represented in polar form. In this form,

the spectrum is the modulas $\sqrt{Re^2 + Im^2}$. The other part, the argument, $\tan^{-1}$ (Im/Re) is called the phase angle. Spectrums are used because they give a view of complex division that is more easily grasped than the use of the complex plane. The phase angles are used in the computation process, but are not shown here.

Let us now consider some improvements in the results presented in Figures 11b, 11c, 12a, and 12b. Signal averaging will be used. A sample "noise" profile obtained from an ensemble of 32 waveforms is illustrated in Figures 14a and 14b. Results for the transfer function and the corresponding inverse deconvolved waveforms are shown in Figure 15b, 16a, 15c, and 16b.

$$O_2' = \frac{I_1 O_2}{I_2}$$

$$O_1' = \frac{I_2 O_1}{I_1}$$

Results in this case are excellent, which can be seen by comparing results in Figure 16a and 16b with those in Figures 7 and 8, respectively.

Concluding Remarks

The study of transducer compensation presented in this paper shows great promise for solving many difficult problems in ultrasonic analysis. Obviously, the work on combining theoretical deconvolution concepts with the "noise" problems associated with real ultrasonic test systems calls for expanded work efforts and analysis. Rather than use a layered media transfer function as illustrated in this paper, it will be necessary to obtain real material and flaw transfer characteristics with very careful and clever ultrasonic data acquisition techniques. The transducer compensation program of study presented here can be used to establish suitable limits on various features associated with transducer characterization, as illustrated in the discussions on comparator and acceptor.

The linearity assumption in our systems model assumes that the pulser and receiver units in a flaw detection instrument can be operated completely independent of each other. An evaluation of the limits and applicability of this assumption calls for a complete understanding of all controls associated with a flaw detection instrument. The quality of the noise considered in this study is of considerable importance, the "noise" in our case being associated with our particular fast data acquisition system utilizing a UTA2 pulser-receiver and a Biomation 8100 analog to digital converter. An evaluation of transducer compensation performance for other test systems and noise components, however, can certainly be carried out with the program of study presented in this paper.

References

1. Seydel, James A., Frederick, Julian R., "A Computer-Processed Ultrasonic Pulse-Echo System", Materials Evaluation, November 1973, Vol. XXXI, No. II.

2. Mucciardi, Anthony N., et al, "Adaptive Nonlinear Signal Processing for Characterization of Ultrasonic NDE Waveforms." Task 1, Inferences of Flat-Bottom Hole Size, USAF Materials Laboratory, Air Force Systems Command, Wright-Patterson AFB, OH, by Adaptronics, Inc., McLean, VA, January 1975.

3. Mucciardi, Anthony N., et al, "Adaptive Nonlinear Signal Processing for Characterization of Ultrasonic NDE Waveforms." Task 2, Measurement of Subsurface Fatigue Crack Size, USAF Materials Laboratory, Air Force Systems Commad, Wright-Patterson AFB, OH, by Adaptronics, Inc., VA, April 1976. Technical REport AFML-TR-76-44.

4. Nabel, E., and Mundry, E., "Evaluation of Echoes in Ultrasonic Testing by Deconvolution", Materials Evaluation, January 1978, Volume 36, No. 1.

5. Brekhovskikh, Leonid M., "Waves in Layered Media", Academic Press, New York, 1972.

Acknowledgments. We would like to thank Krautkramer-Branson, Inc. for their computer support and enthusiasm to carry out this work, and also the Ground Support Equipment Department of the Naval Air Engineering Center, Lakehurst, New Jersey, for the support of this project.

Computer Deconvolution Procedure

Consider the complex multiplication

$$(a + jb)(c + jd) = (e + jf)$$

where a, b, e, and f are known values, c and d are to be found (transfer function).

$$ac - bd = e \qquad \text{(real parts equal)}$$

$$bc - ad = f \qquad \text{(imaginary parts equal)}$$

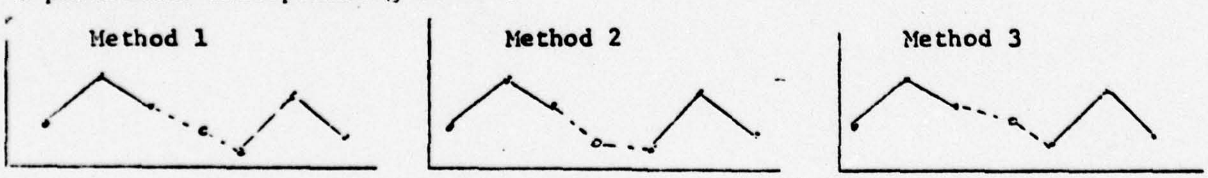
Rewrite as

$$\begin{bmatrix} a & -b \\ b & a \end{bmatrix} \begin{bmatrix} c \\ d \end{bmatrix} = \begin{bmatrix} e \\ f \end{bmatrix}$$

then if $a^2 + b^2 \neq 0$ (Determinant non-zero), the solution for the system is

$$\frac{1}{a^2 + b^2} \begin{bmatrix} a & b \\ -b & a \end{bmatrix} \begin{bmatrix} e \\ f \end{bmatrix} = \begin{bmatrix} c \\ d \end{bmatrix} \qquad \text{(uniquely)}$$

The literals may be considered as subscripted variables or array variables. The values for c and d may be calculated each time $a^2 + b^2 = 0$. The sequences c and d now are determined except for "holes" at the locations where $a^2 + b^2 \neq 0$. A mathematical argument* requires that three "holes" be filled with interpolated values. The interpolation scheme then becomes critical. It seems the only available criteria to date is one based on comparisons between analytically generated transfer functions and ones obtained with the above process using a particular interpolating scheme.



*If e = a, f = b, the division of two identical complex numbers, although $a^2 + b^2 = 0$ at times would require the continuous result 1.

Table I - Sample Brekhovskikh Layered Media Transfer Function Parameters

	density gm/cm^3	wave velocity cm/ sec	thickness cm
layer 1	2.71	.63	.0336
layer 2	1.18	.27	.0168
layer 3	2.71	.63	.0336

Table II - Sample Ultrasonic Input Waveforms Obtained from Real Experimental Data

	Center Frequency MHz	6 dB down Bandwidth MHz	6 dB down Center Frequency MHz
Function #1	3.81	3.22	3.47
Function #2	5.18	2.05	5.32

Fig. 1a - A Basic Deconvolution Model

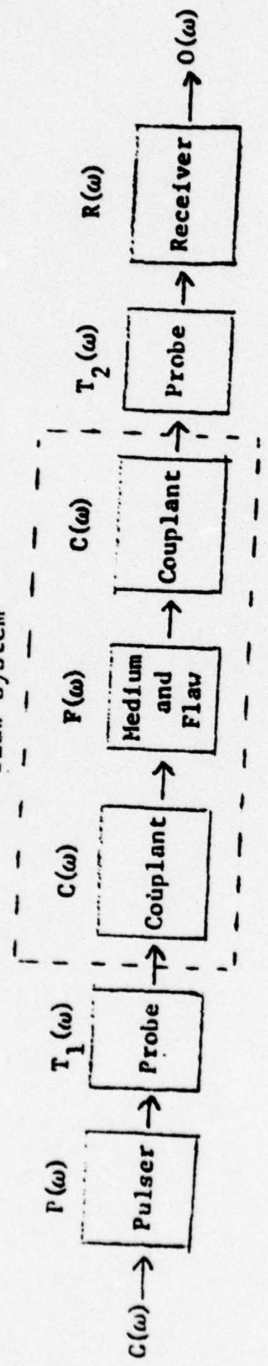


Fig. 1b - Generalized Ultrasonic Test System

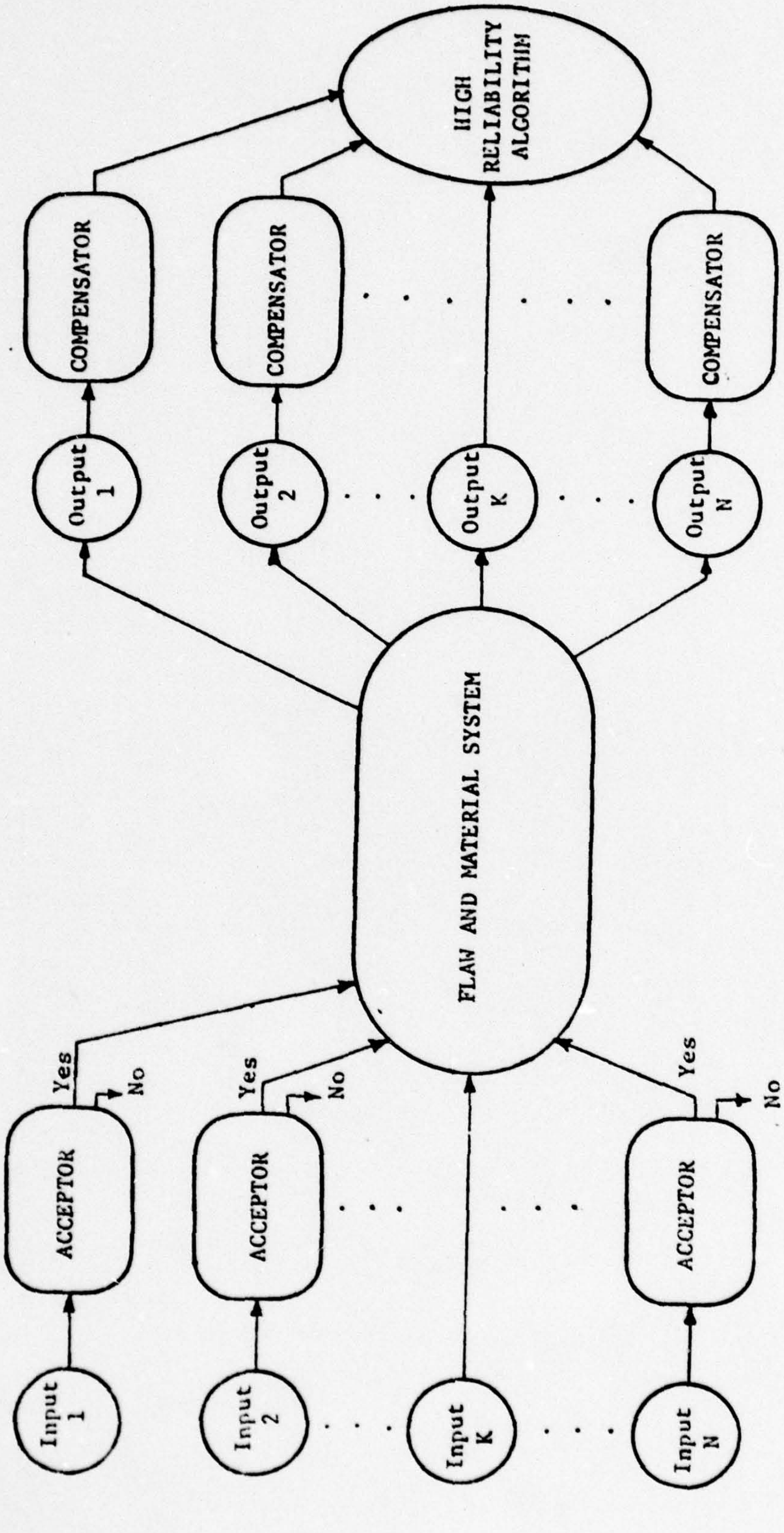


Fig. 2 - General Compensation Concept

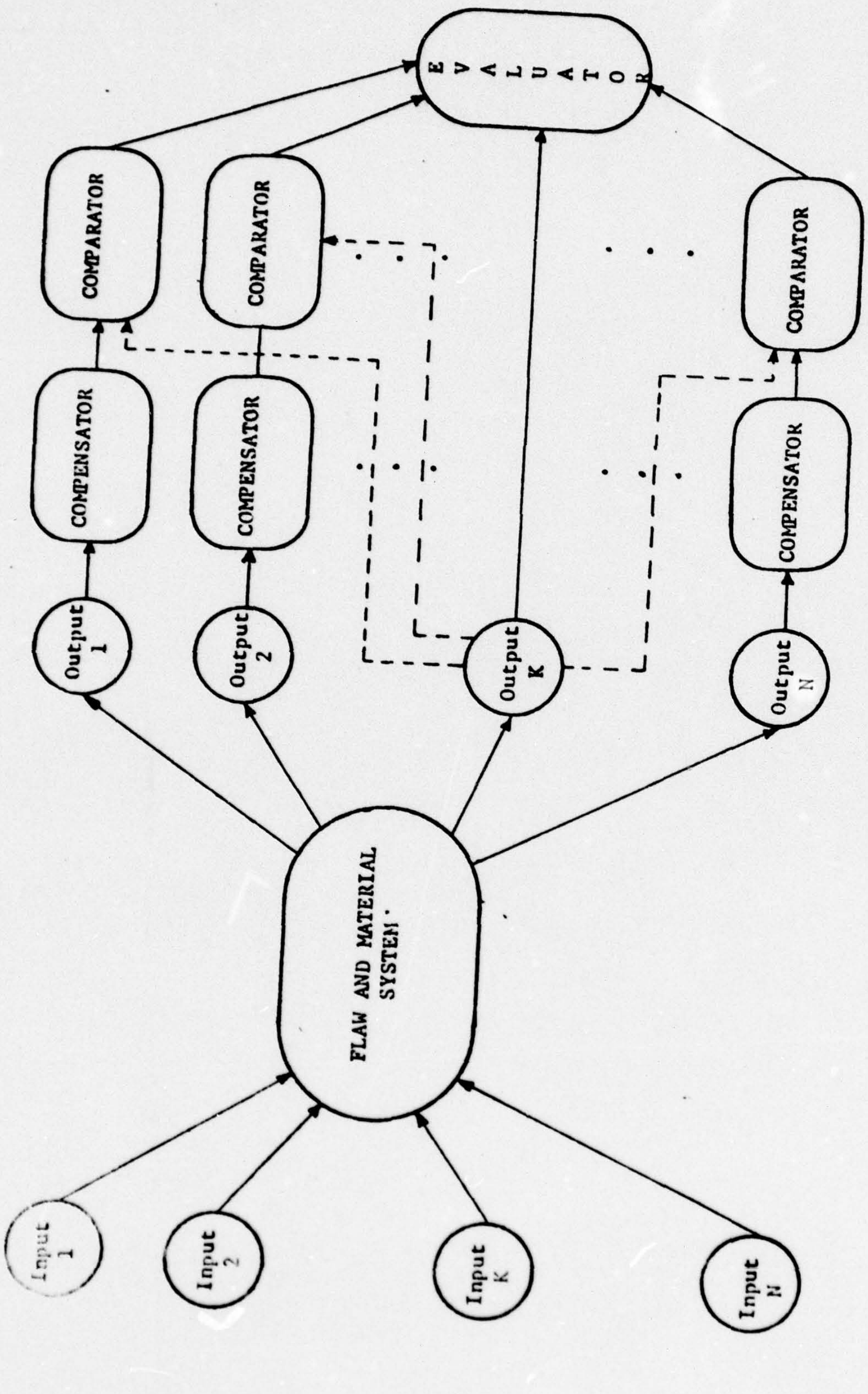


Fig. 3 - Acceptor Design Concept

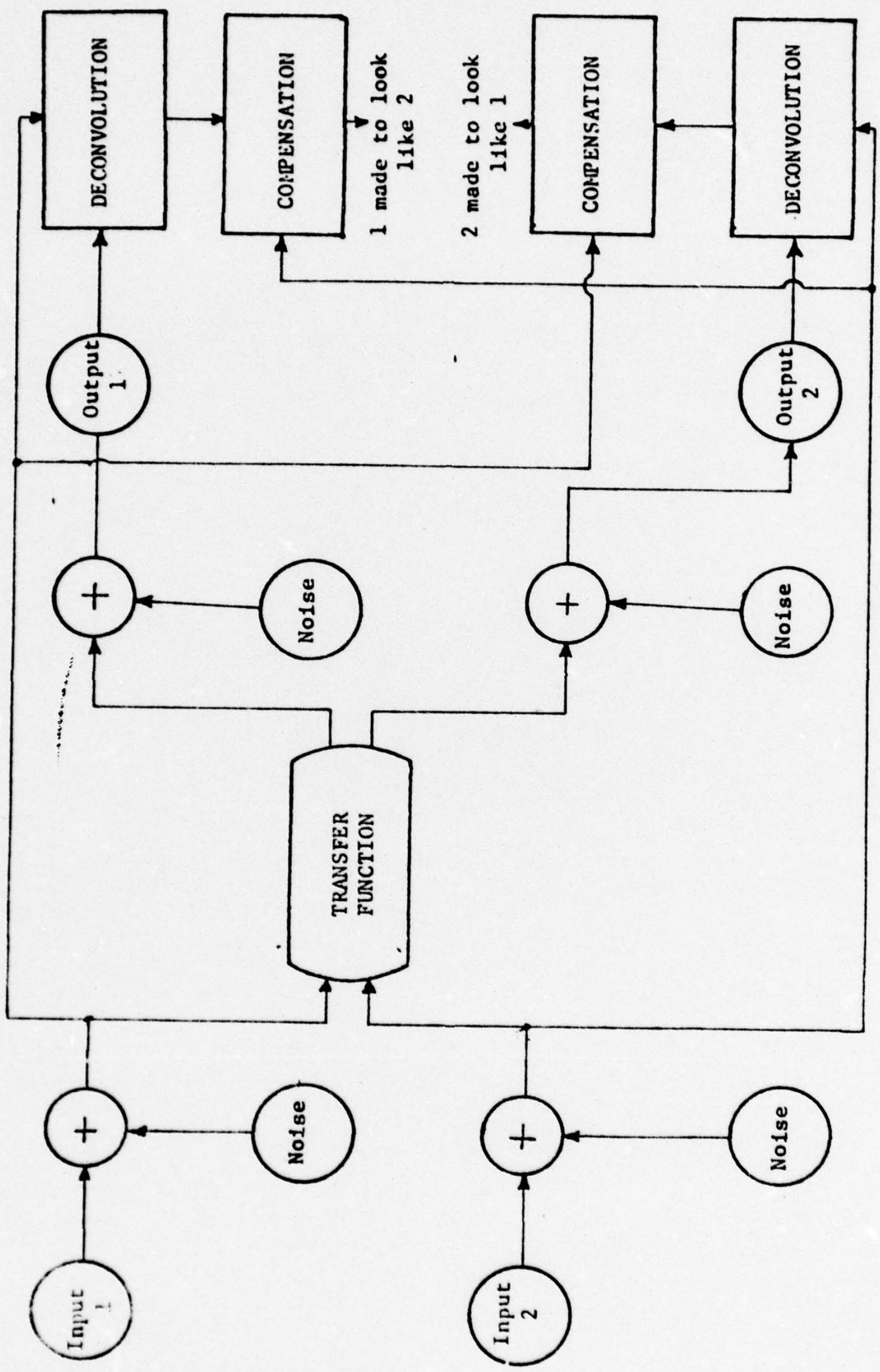


Fig. 4 - General Scheme of the Paper

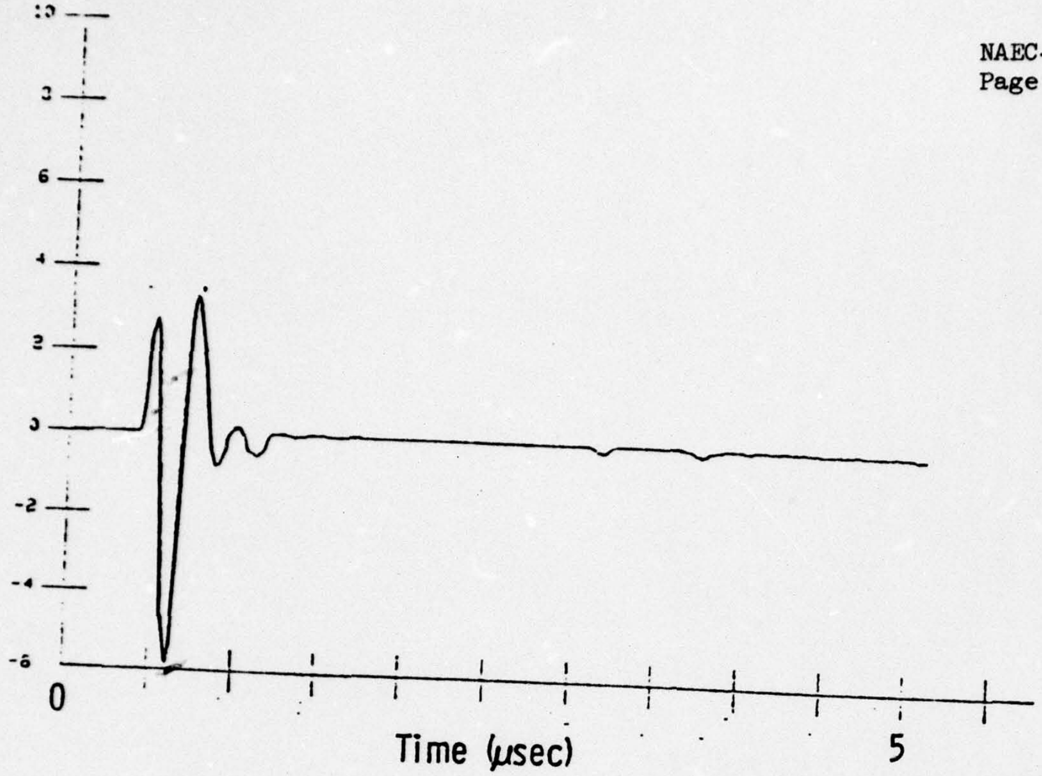


Fig. 5a - Input Function One

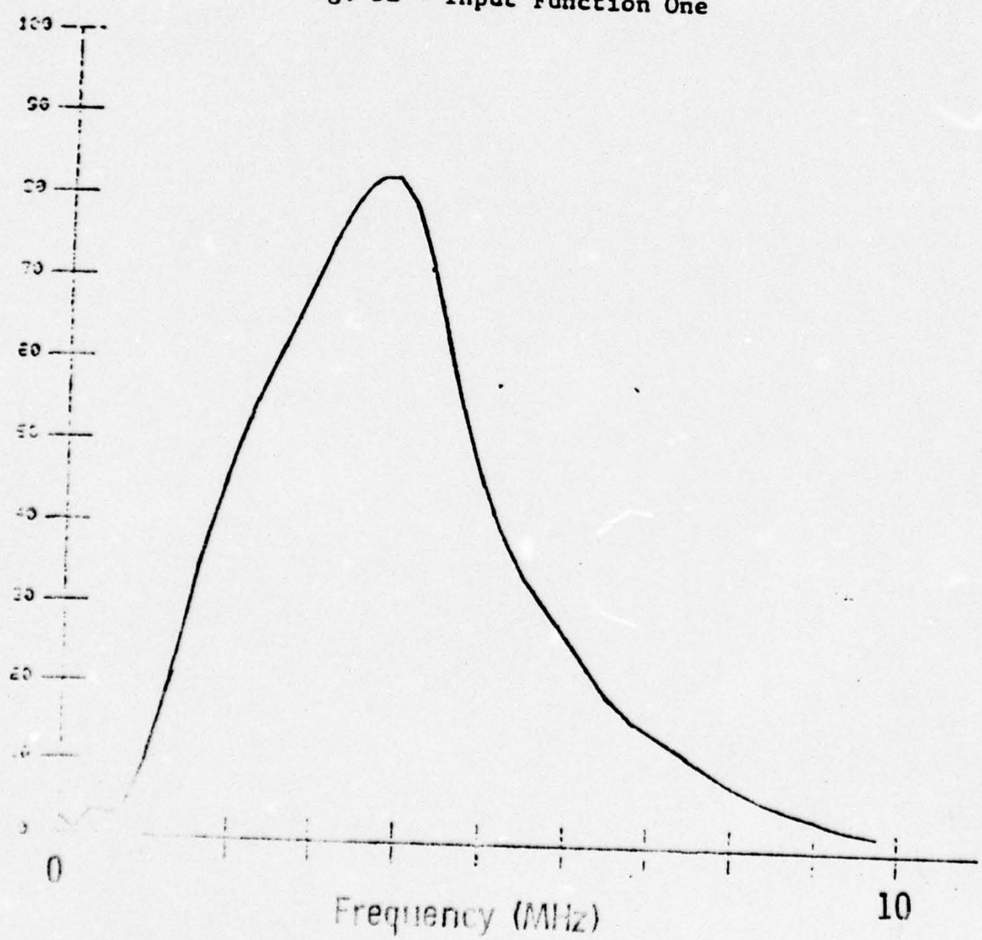


Fig. 5b - Spectrum of Input One

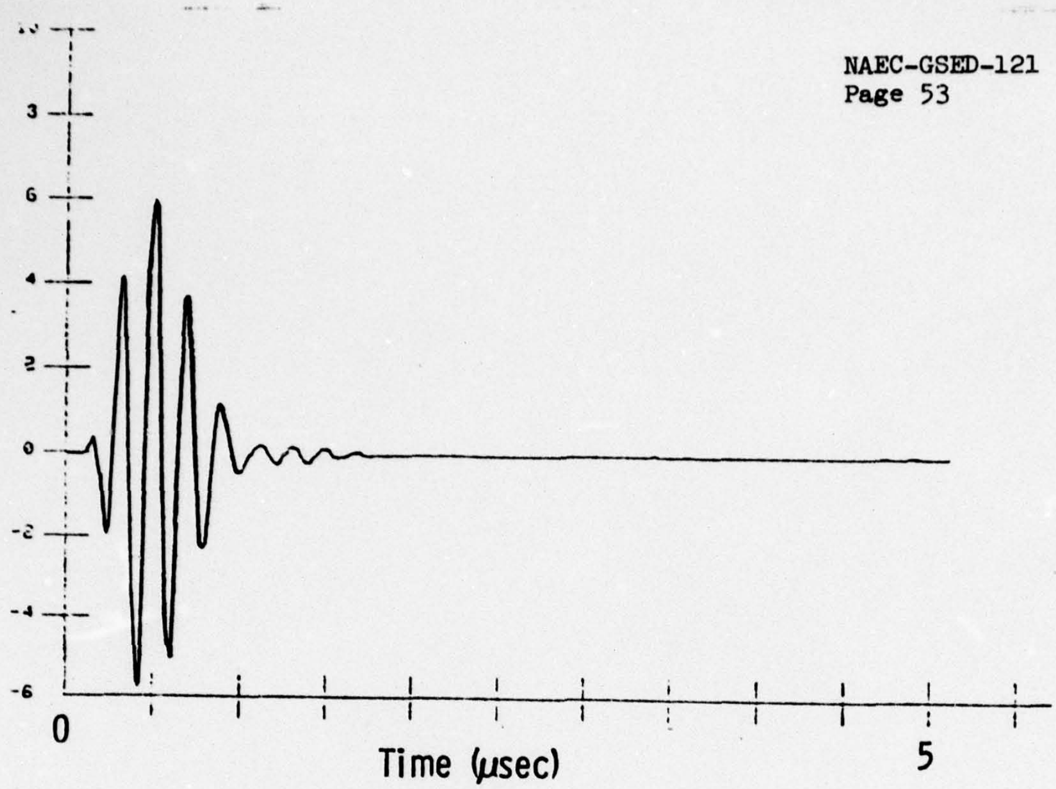


Fig. 6a - Input Function Two

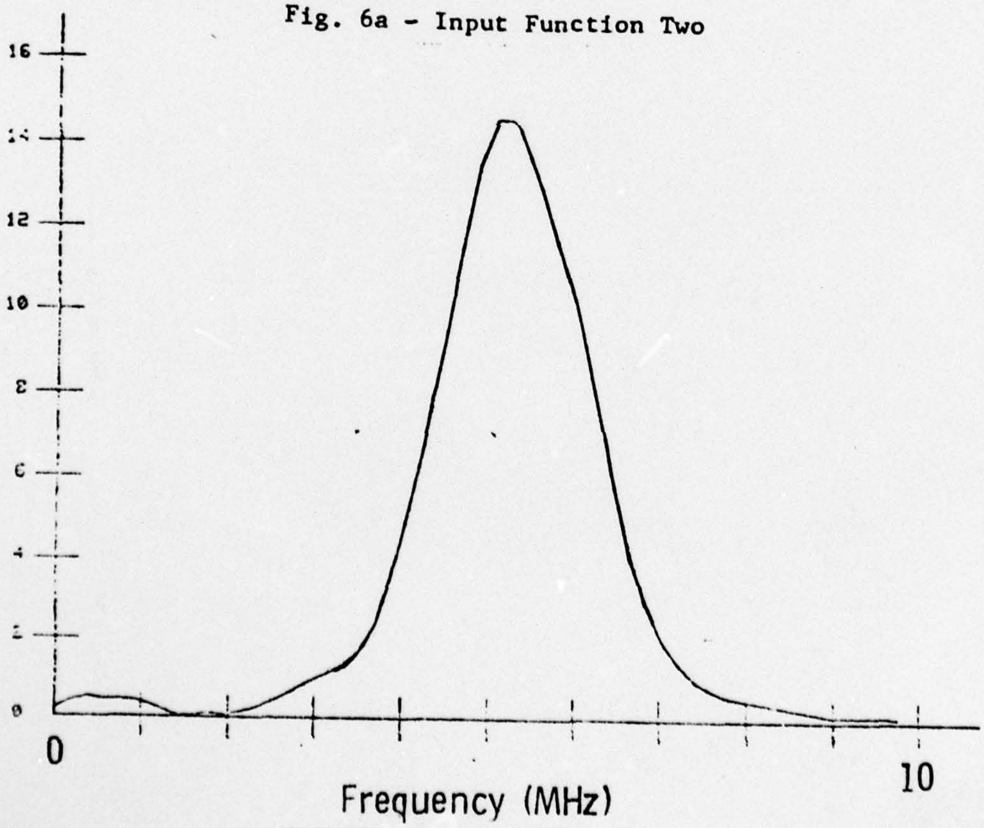


Fig. 6b - Spectrum of Input Two

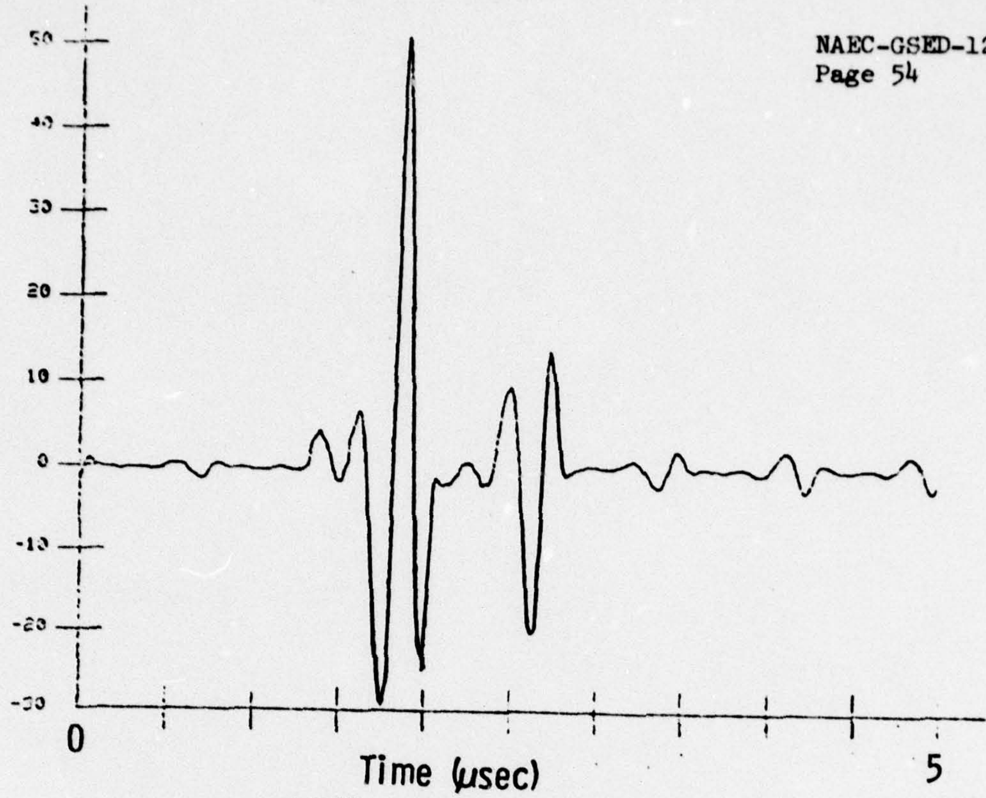


Fig. 7a - Output Function One

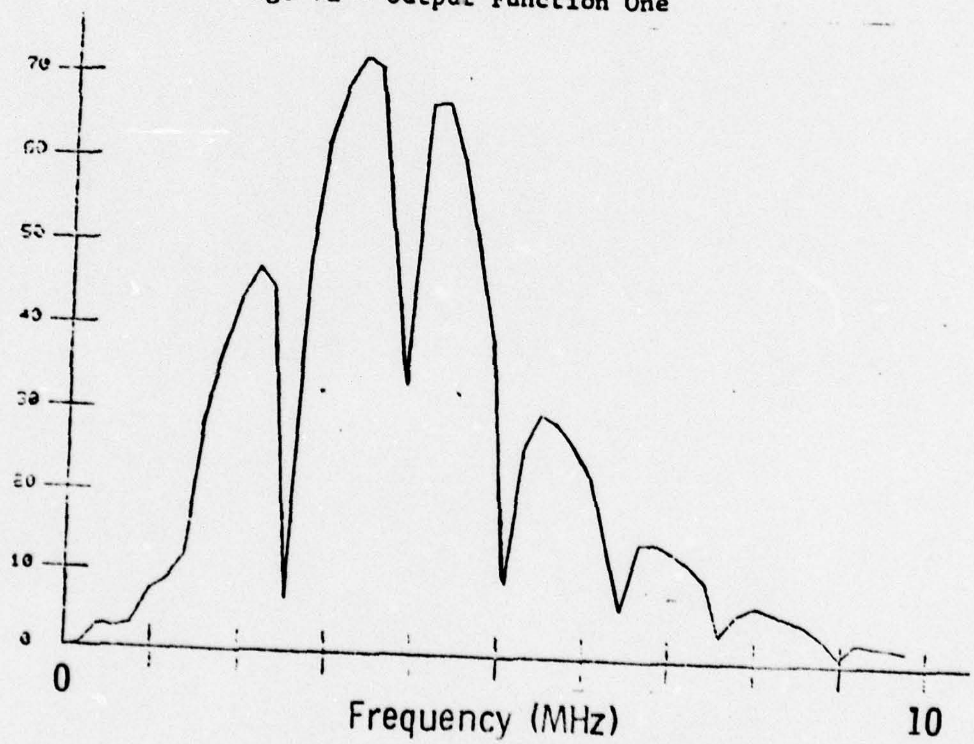


Fig. 7b - Spectrum of Output One

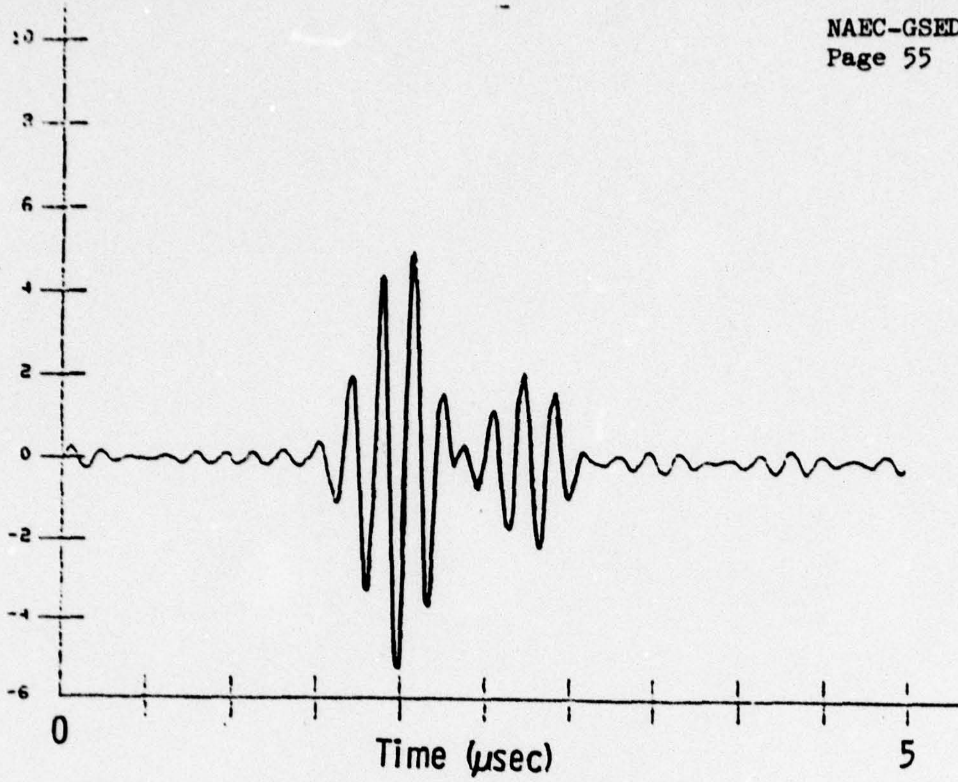


Fig. 8a - Output Function Two

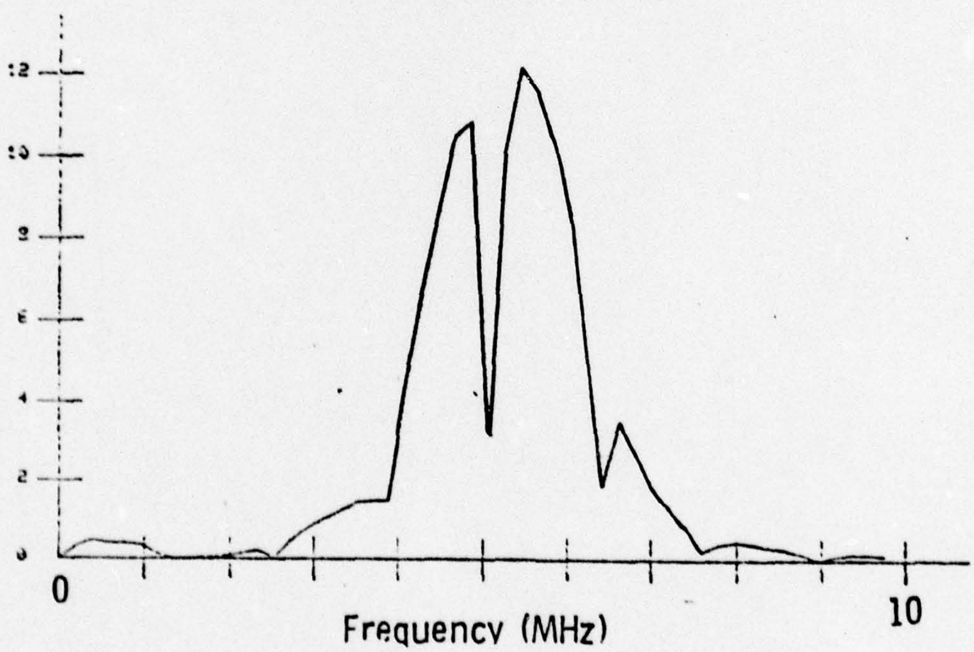


Fig. 8b - Spectrum of Output Two

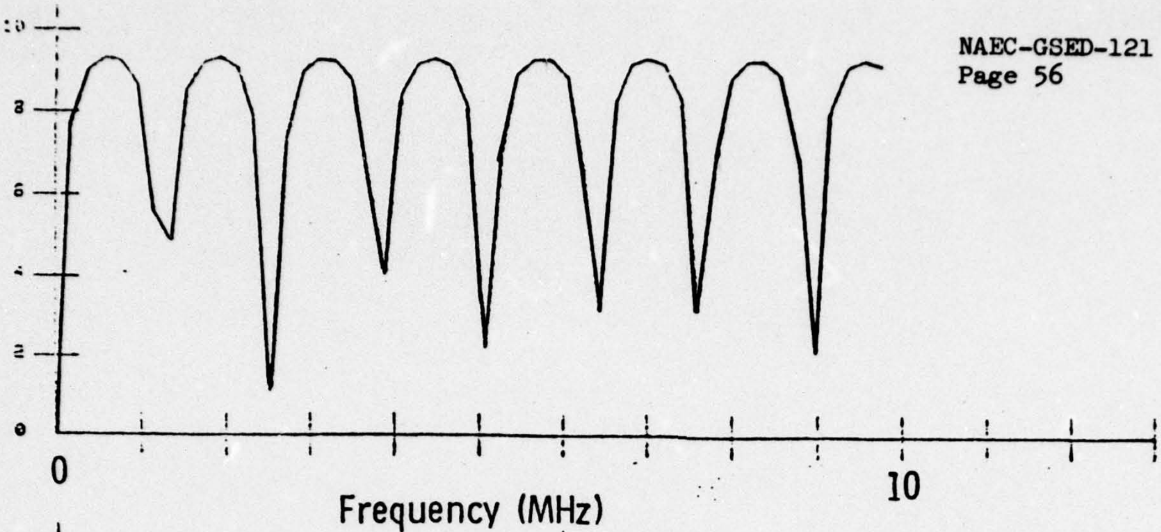


Fig. 9a - Theoretical Transfer Function for a Sample Layered Media Problem

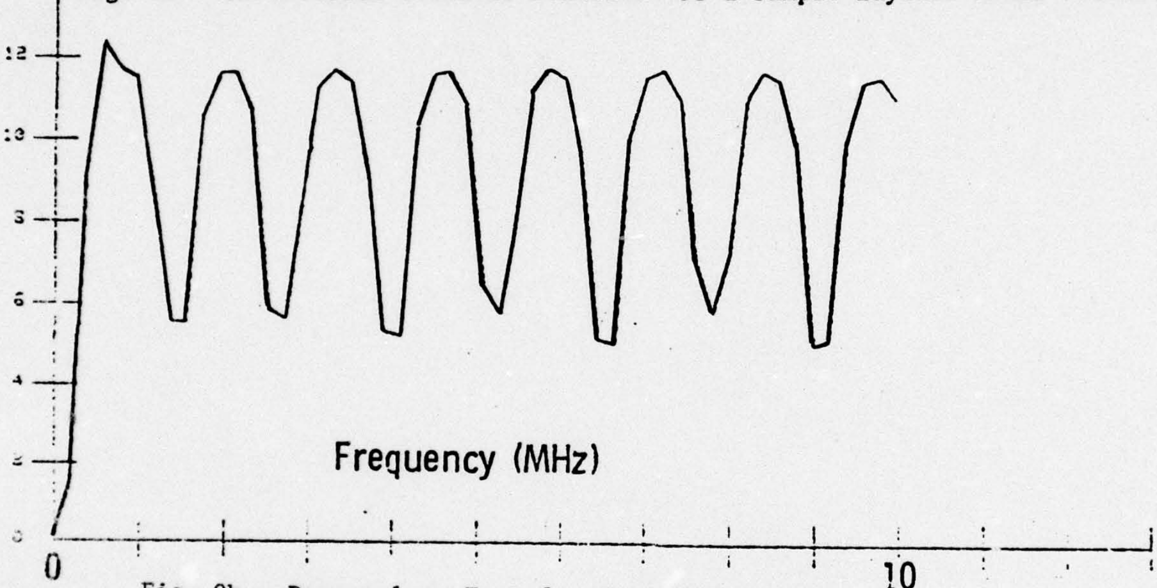


Fig. 9b - Deconvolved Transfer Function (O_1/I_1)
(showing mathematical noise)

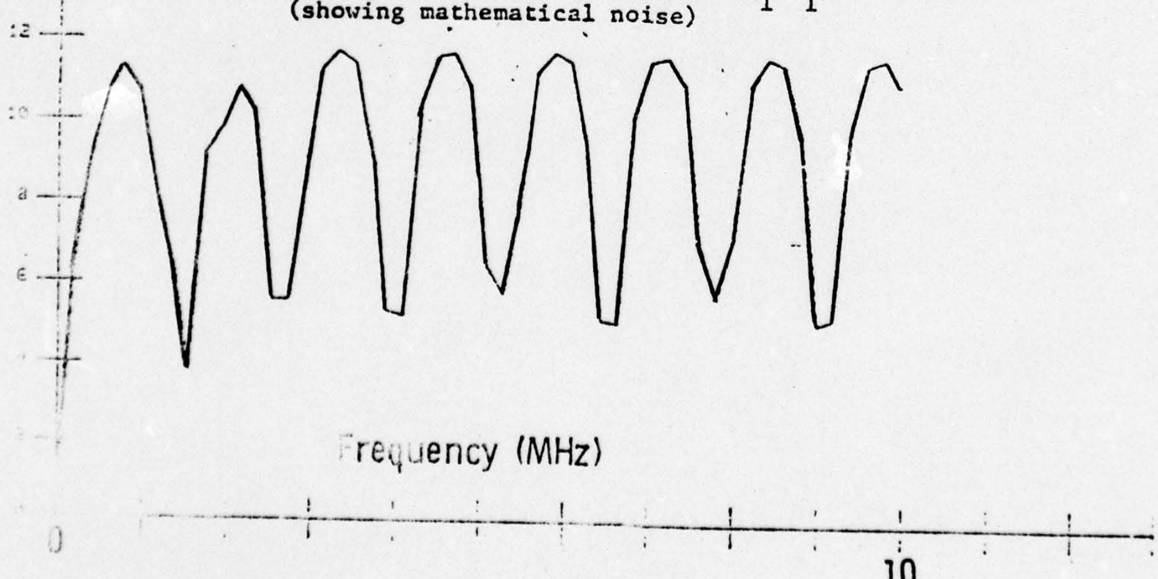


Fig. 9c - Deconvolved Transfer Function (O_2/I_2)
(showing mathematical noise)

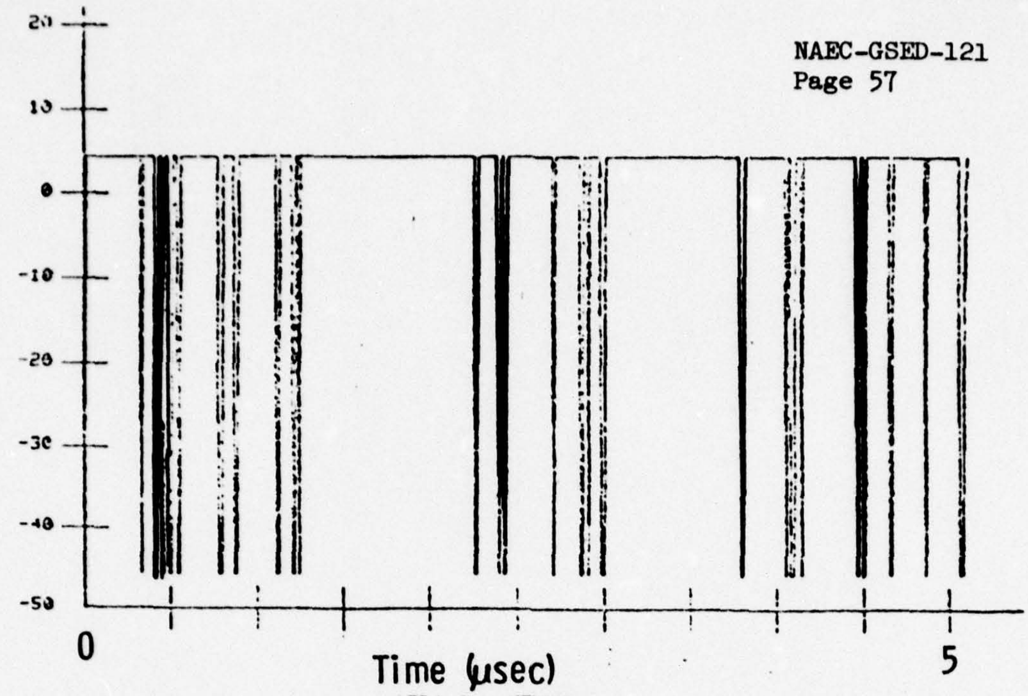


Fig. 10a - Sample Noise 1

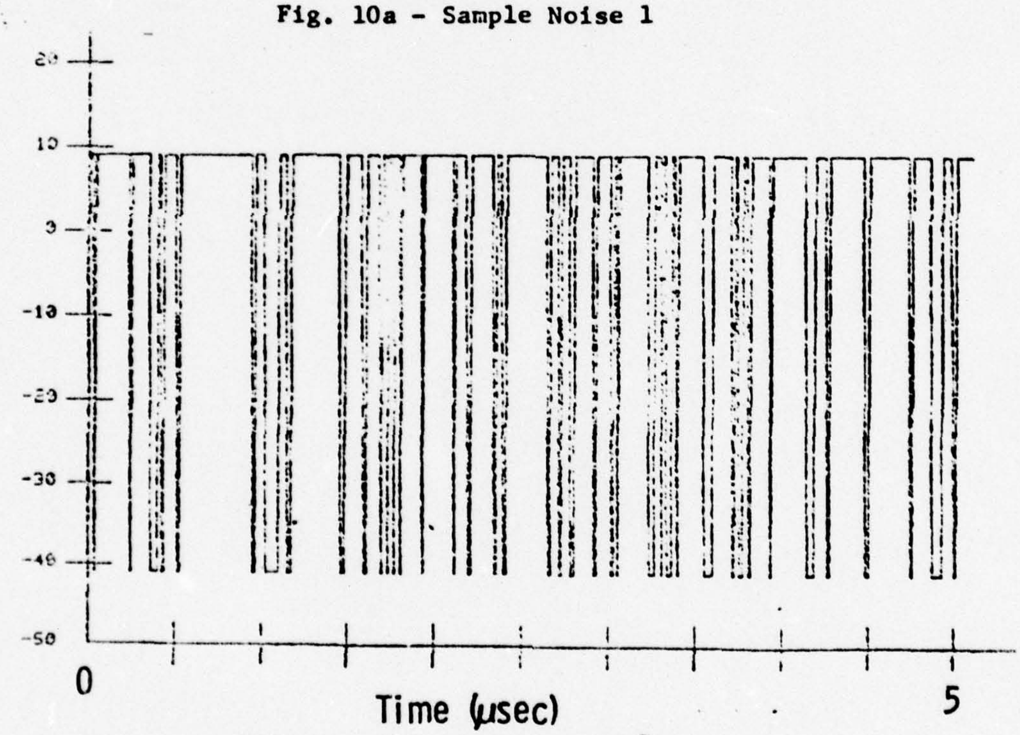


Fig. 10b - Sample Noise 2

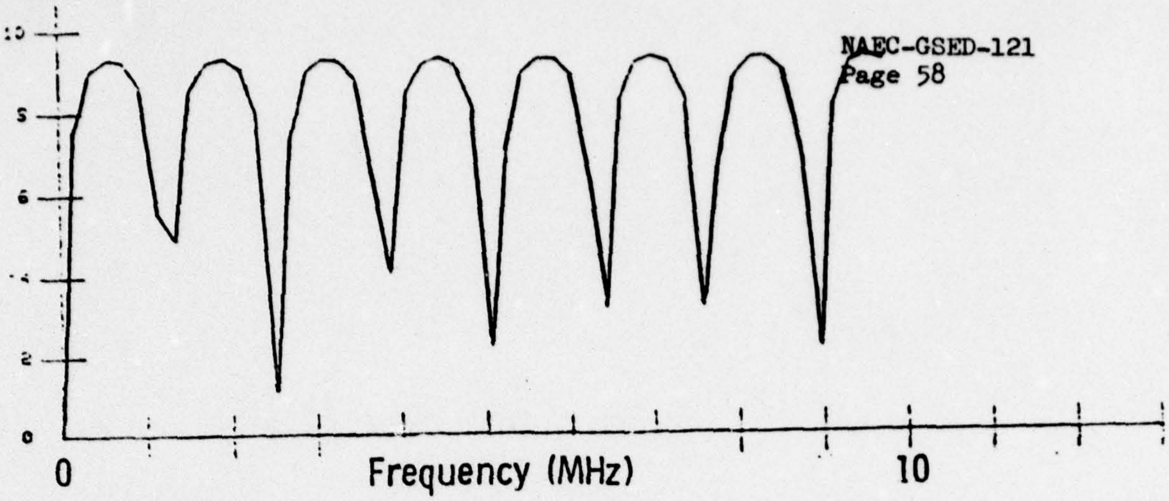


Fig. 11a - Theoretical Transfer Function for a Sample Layered Media Problem

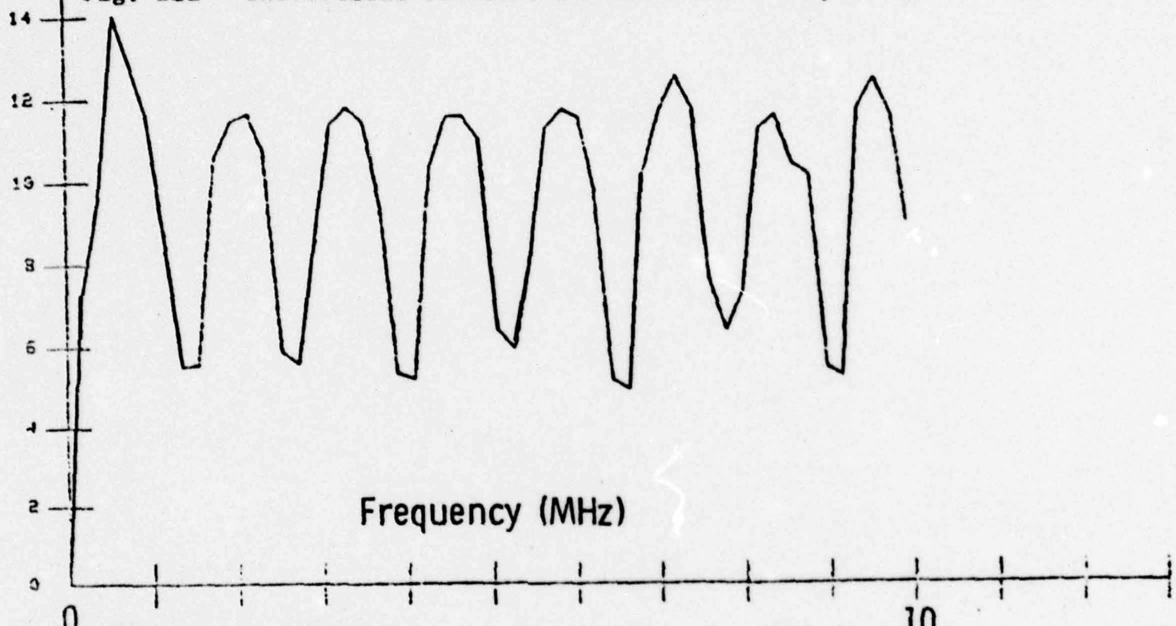


Fig. 11b - Deconvolved Transfer Function (O_1/I_1)
(showing system noise)

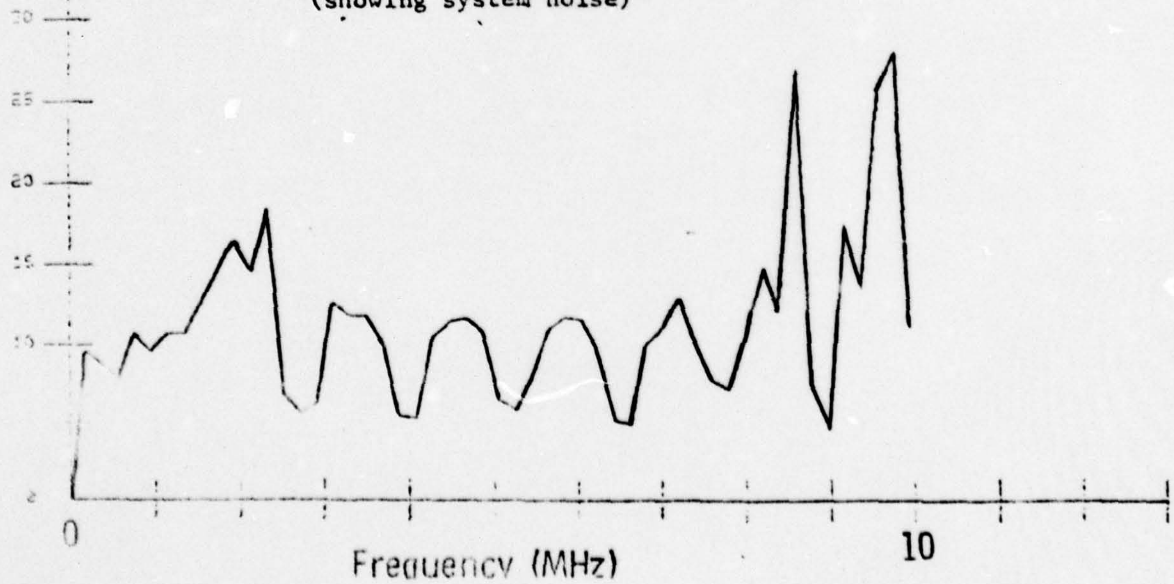


Fig. 11c - Deconvolved Transfer Function (O_2/I_2)
(showing system noise)

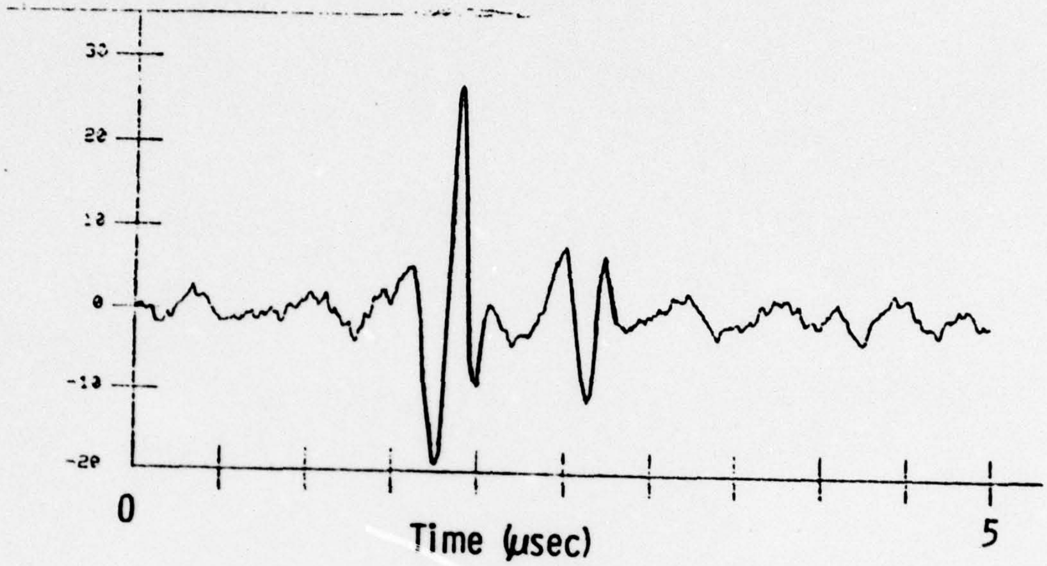


Fig. 12a - Deconvolved Result with Noise
(making Output Function Two look like Output Function One)

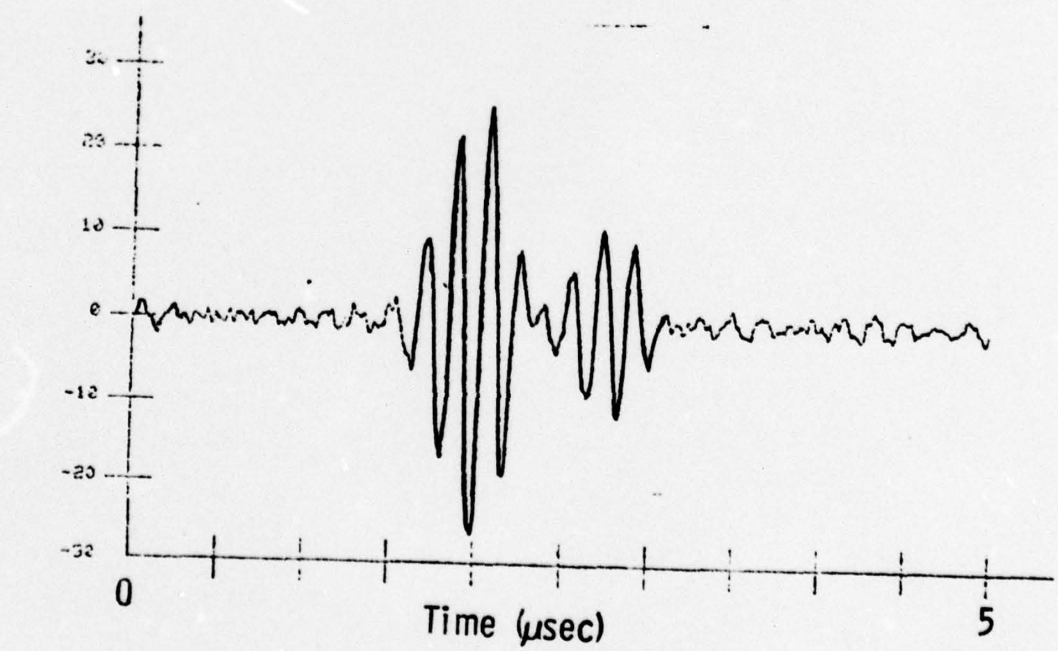


Fig. 12b - Deconvolved Result with Noise
(making Output Function One look like Output Function Two)

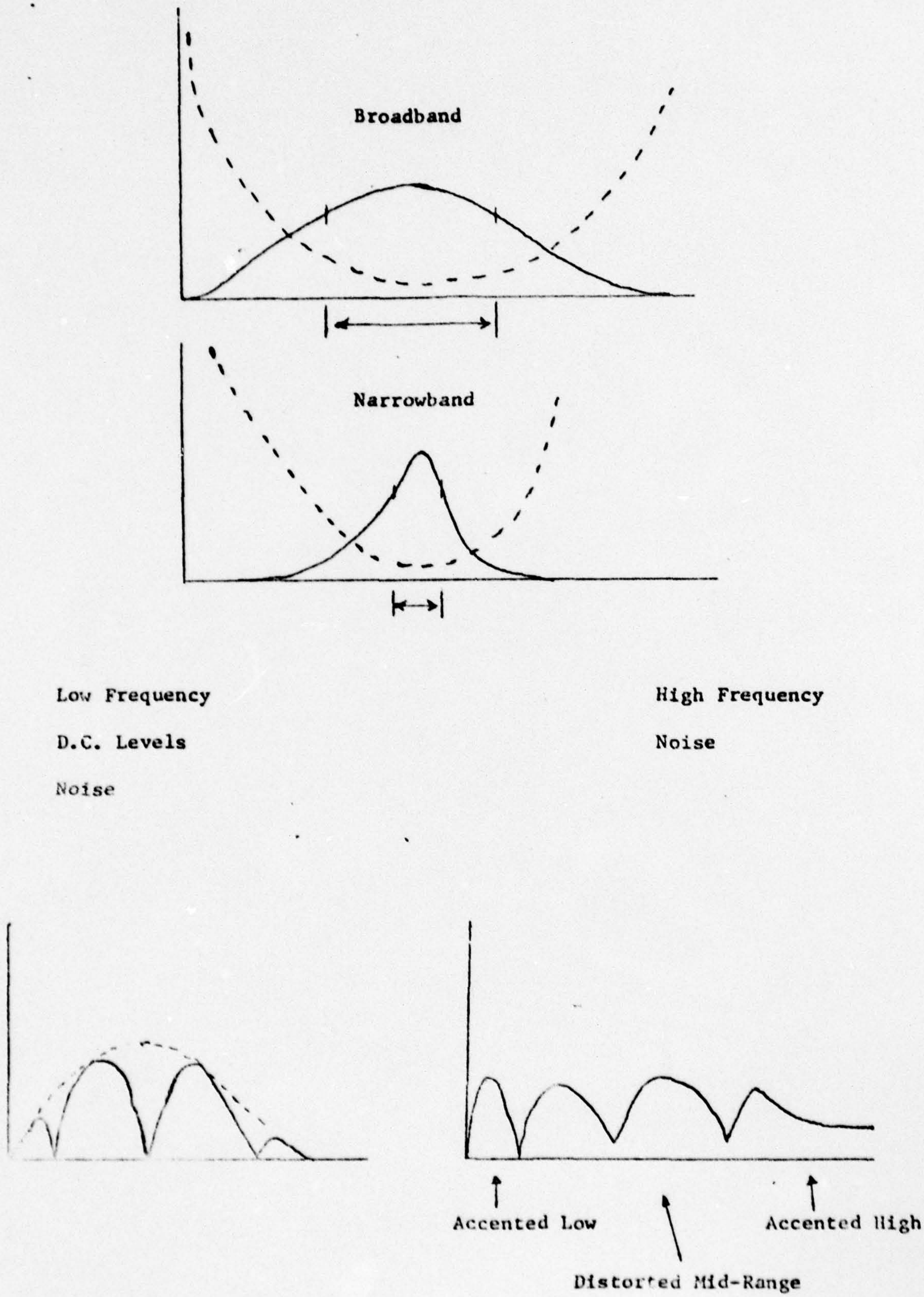


Fig. 13 - Illustration of the Deconvolution Process

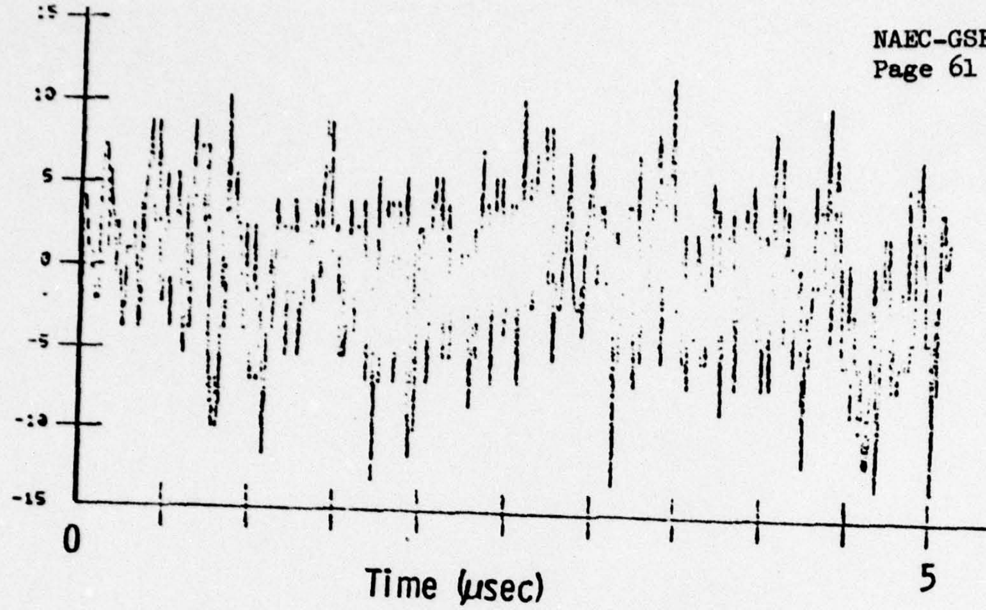


Fig. 14a - Sample of Averaged Noise 1

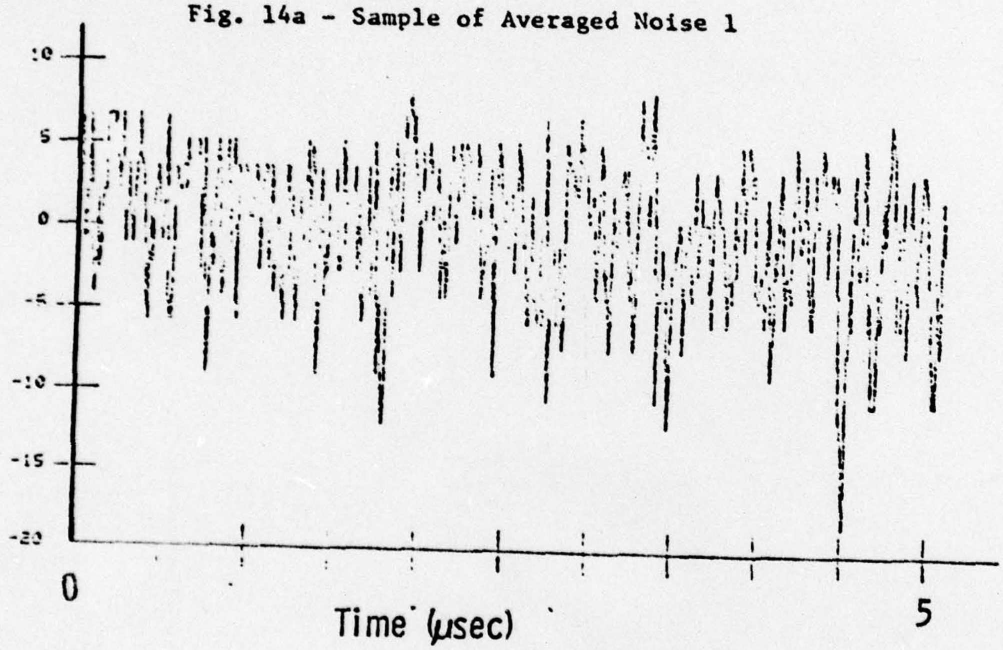


Fig. 14b - Sample of Averaged Noise 2

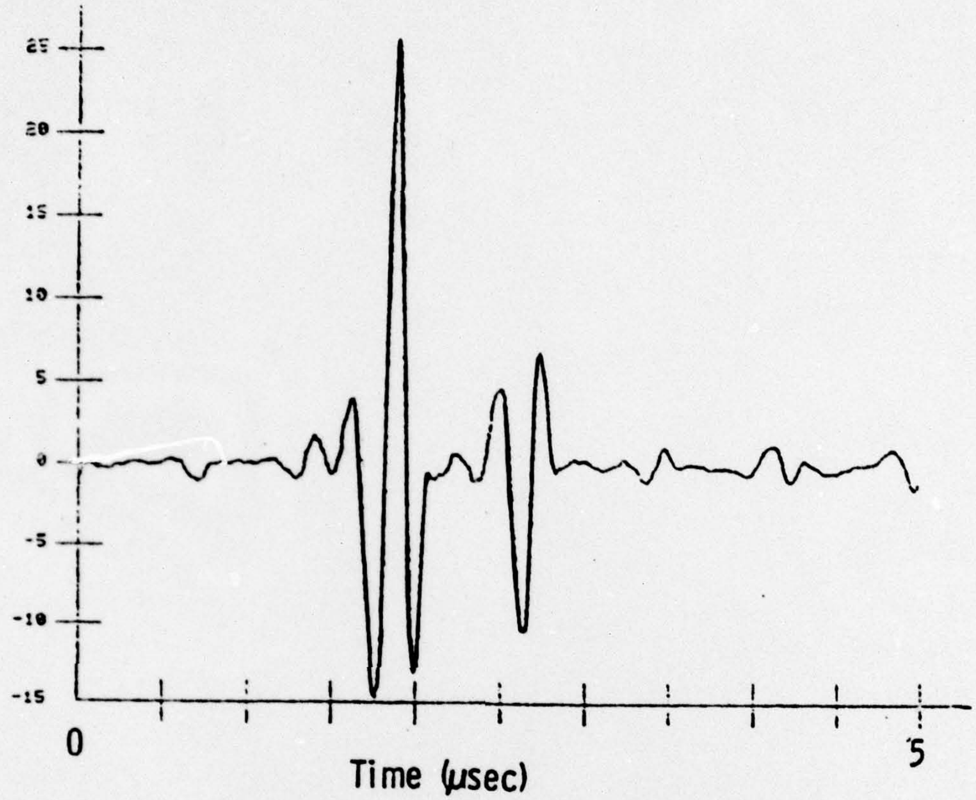


Fig. 16a - Deconvolved Result with Averaged Noise
(making Output Function Two look like Output Function One)

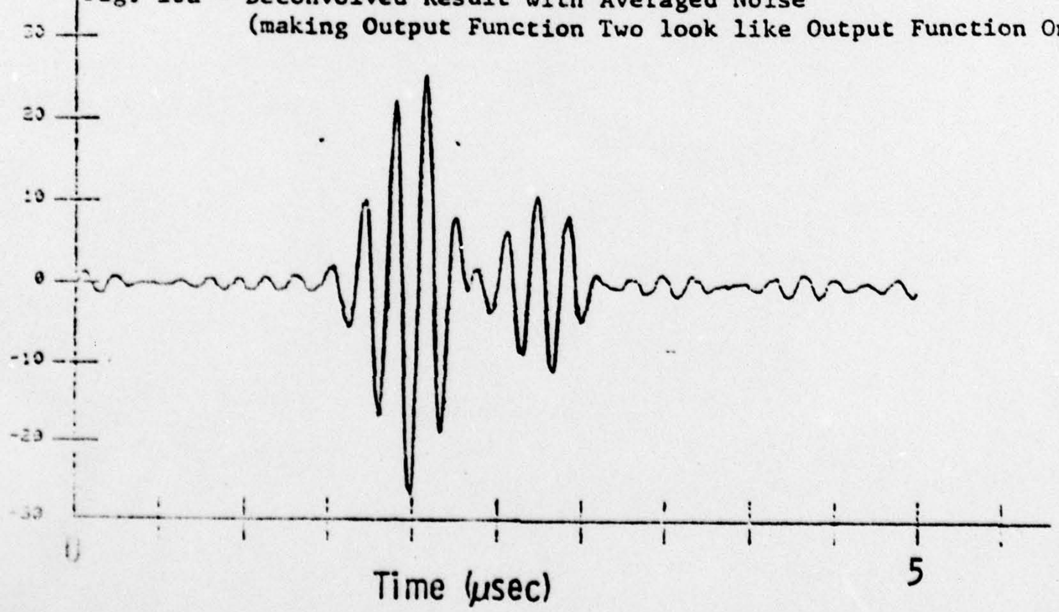


Fig. 16b - Deconvolved Result with Averaged Noise
(making Output Function One look like Output Function Two)

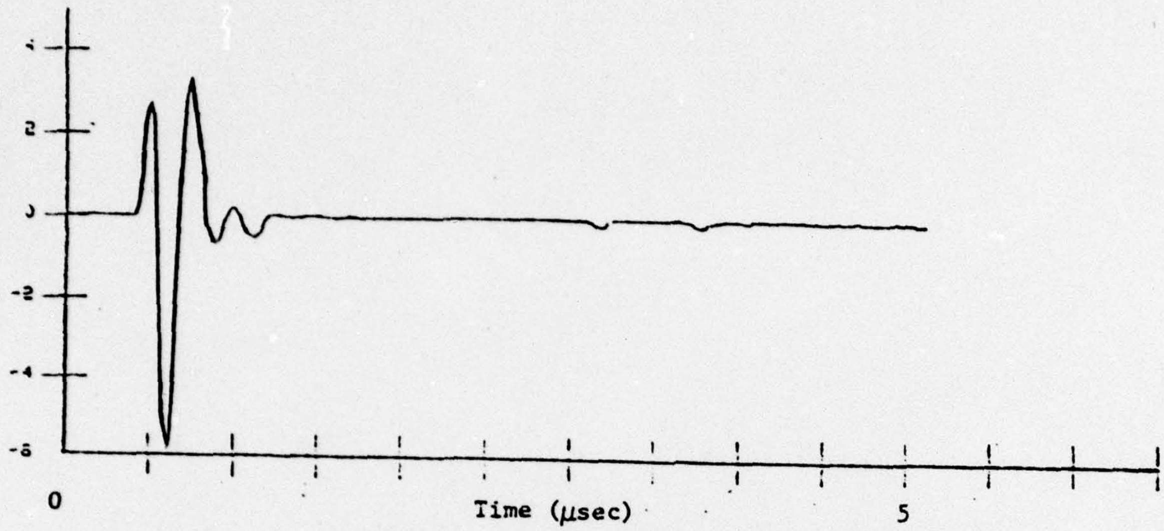


Fig. 5a - Input Function One

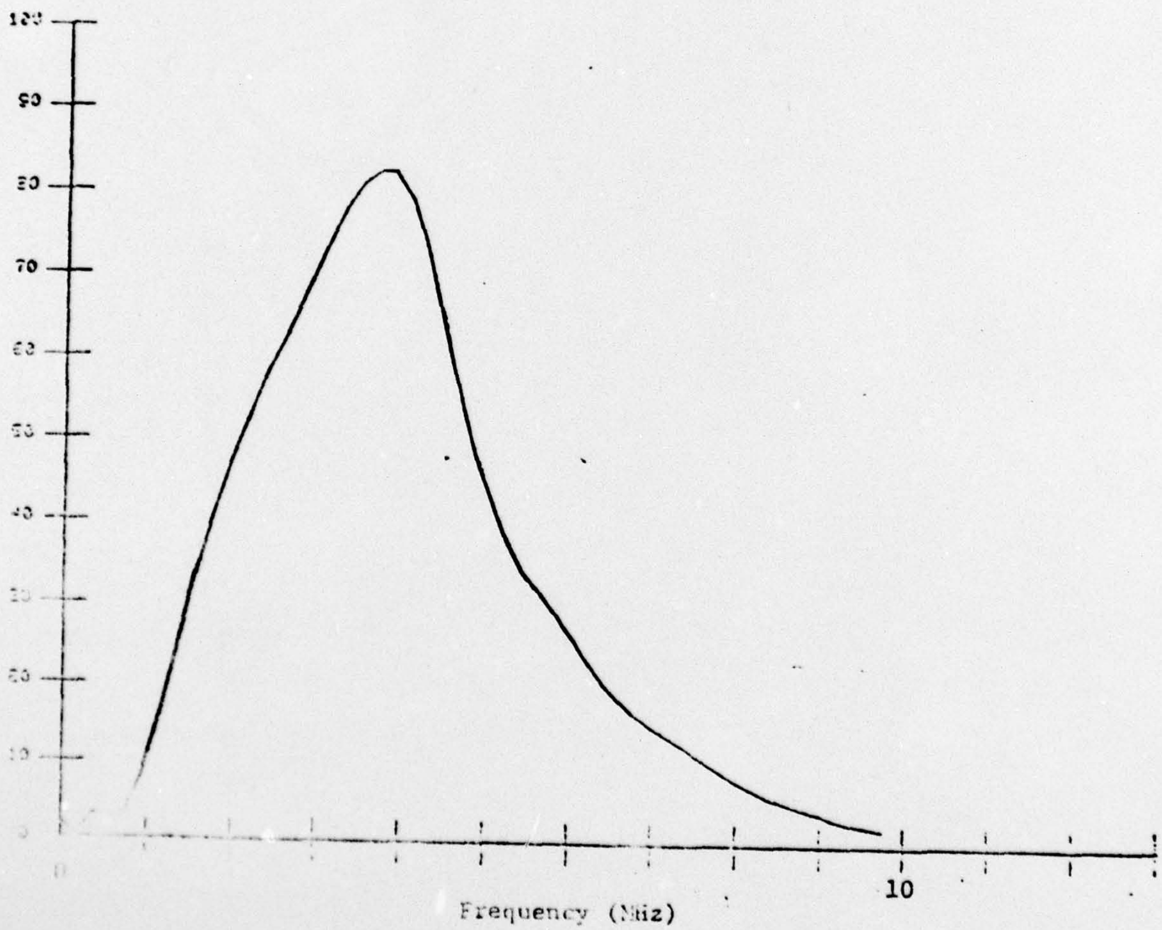


Fig. 5b - Spectrum of Input One

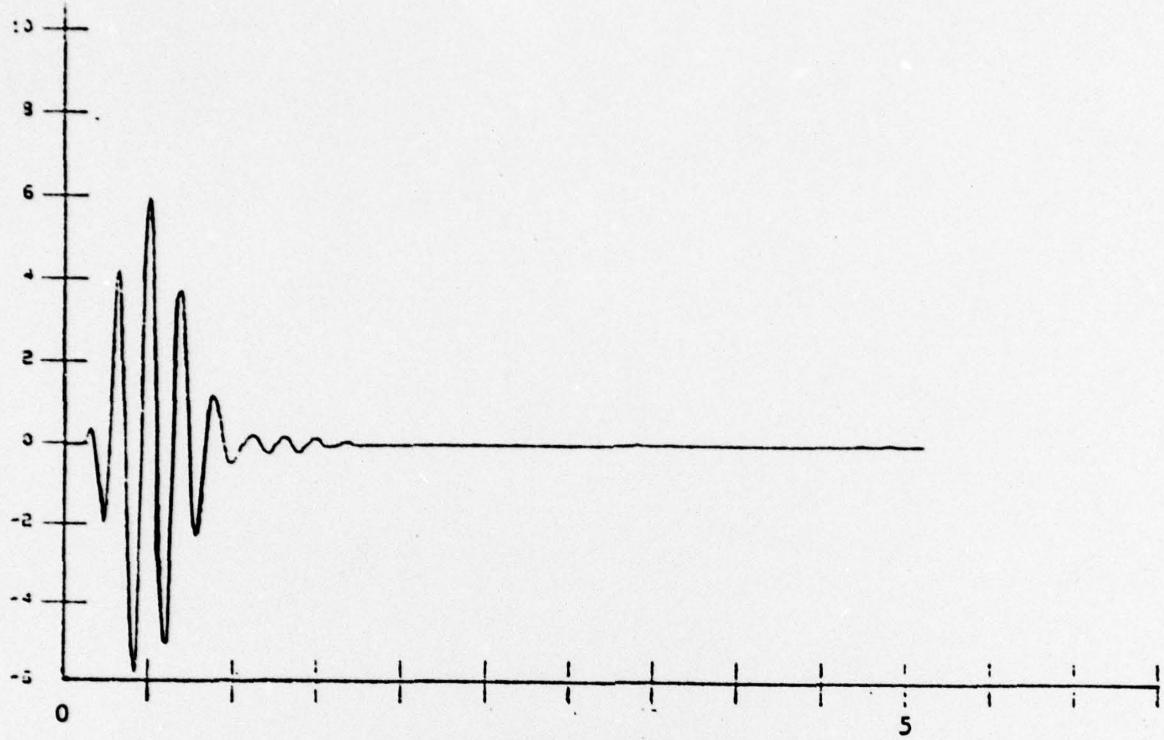


Fig. 6a - Input Function Two

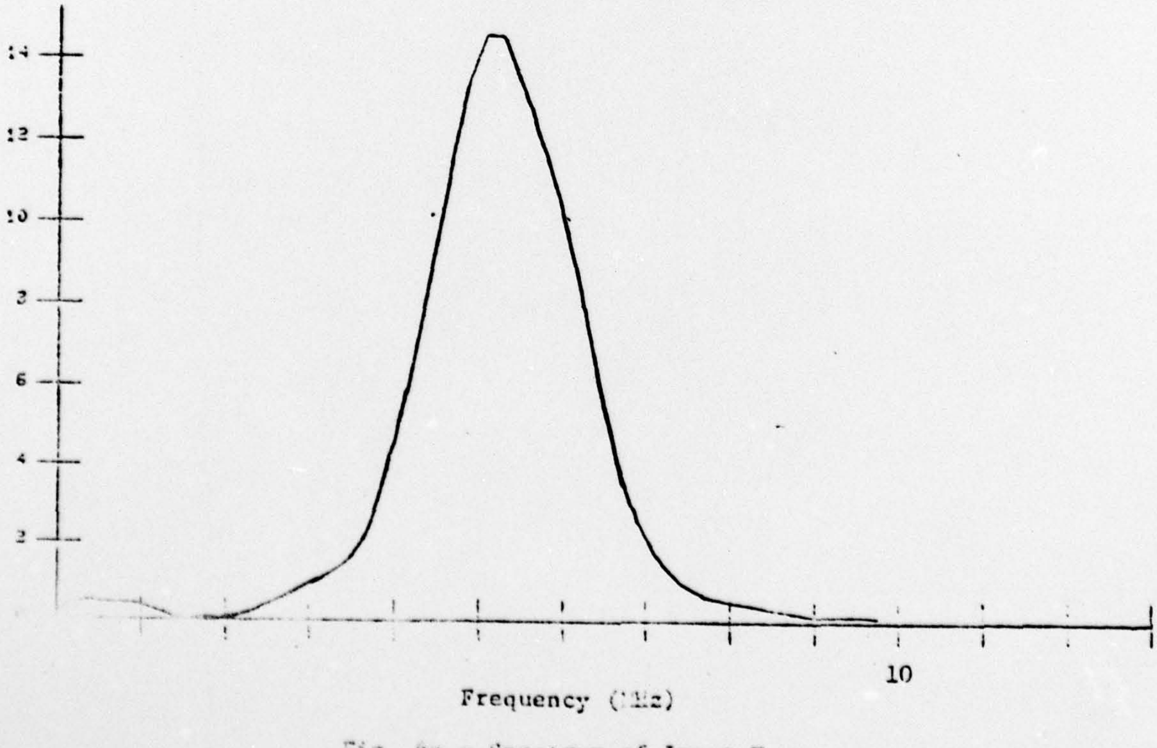


Fig. 6b - Spectrum of Input Two

Fig. 7a - Output Function One

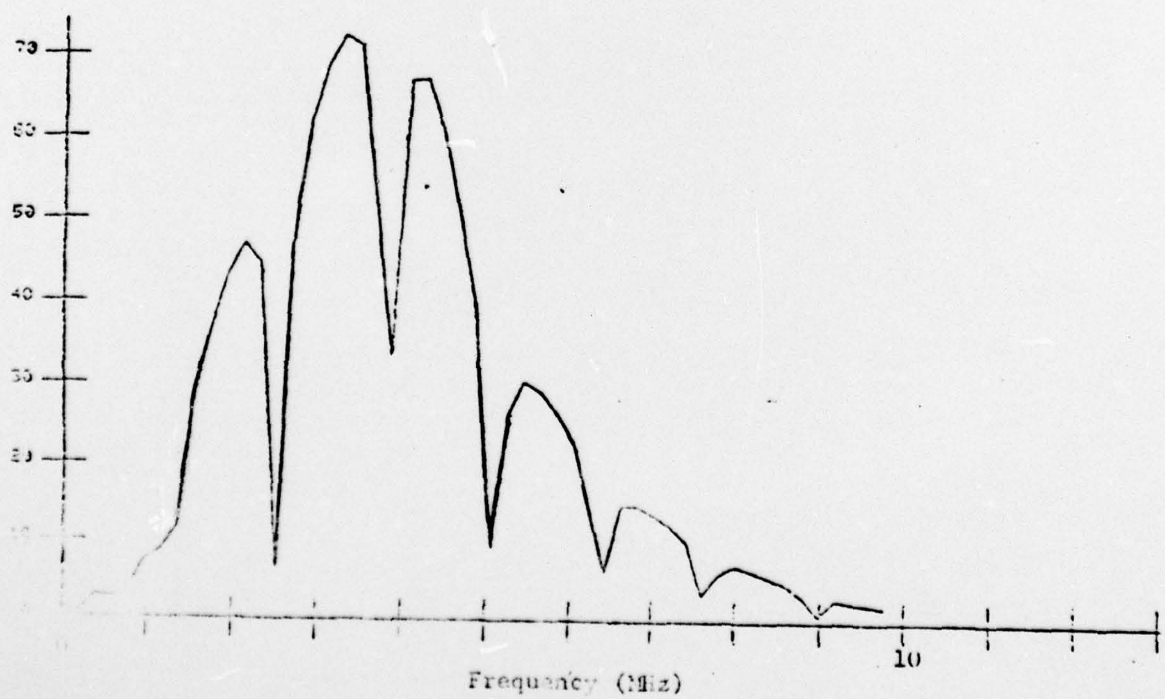


Fig. 7b - Spectrum of Output One

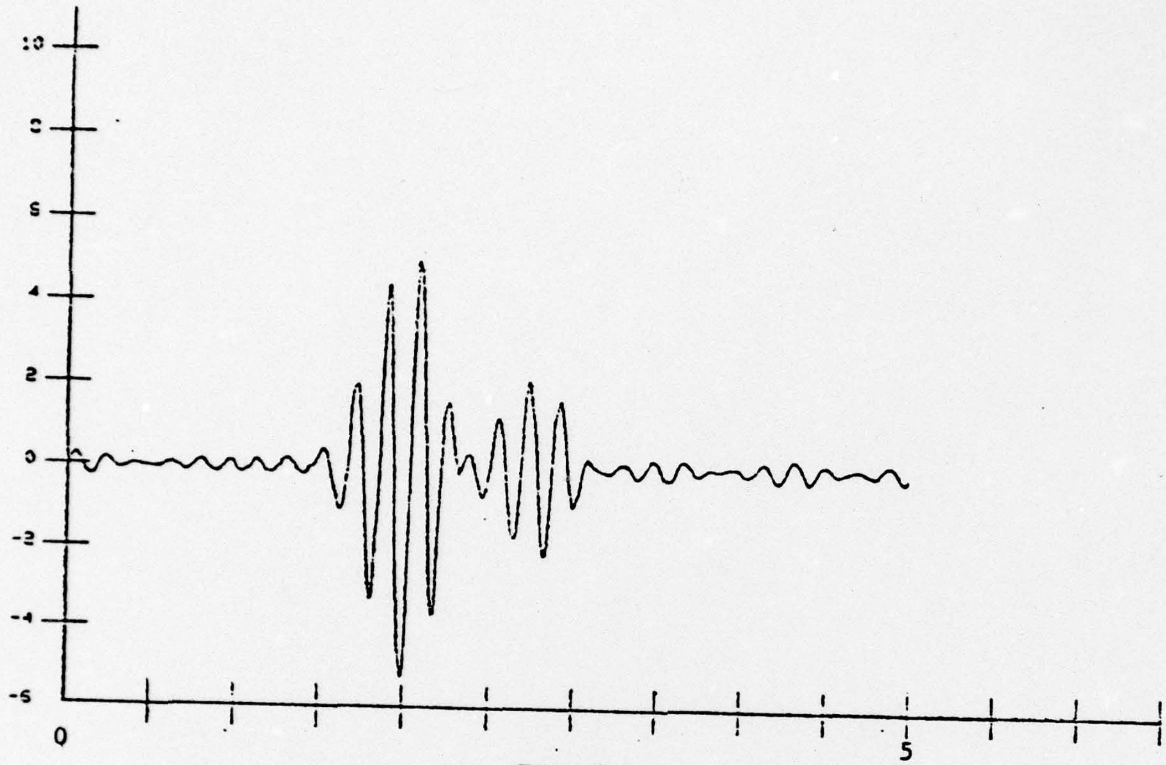


Fig. 8a - Output Function Two

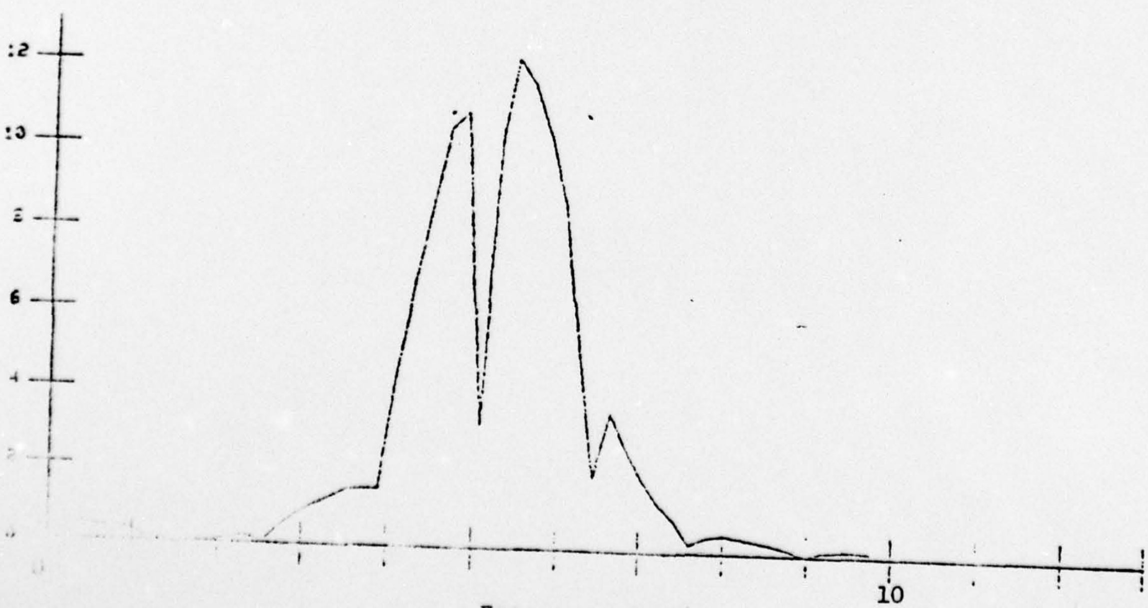


Fig. 8b - Spectrum of Output Two

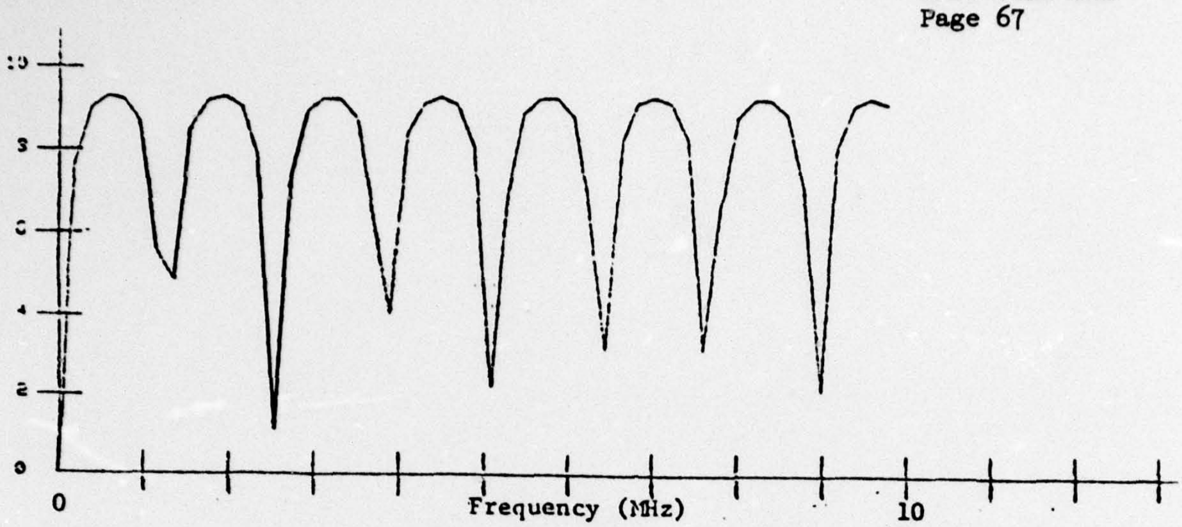


Fig. 9a - Theoretical Transfer Function for a Sample Layered Media Problem

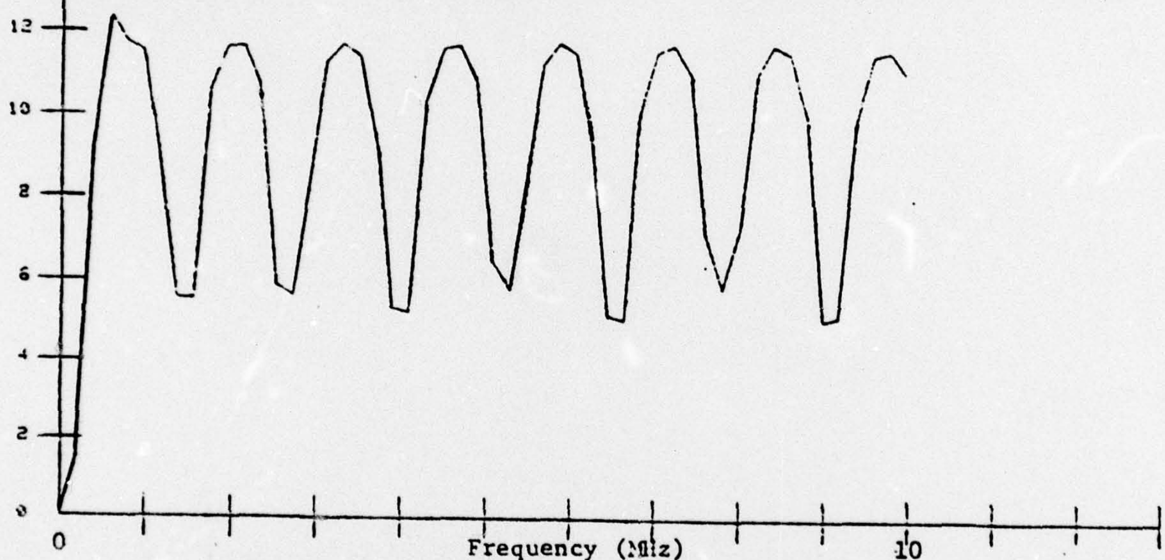


Fig. 9b - Deconvolved Transfer Function (O_1/I_1)
(showing mathematical noise)

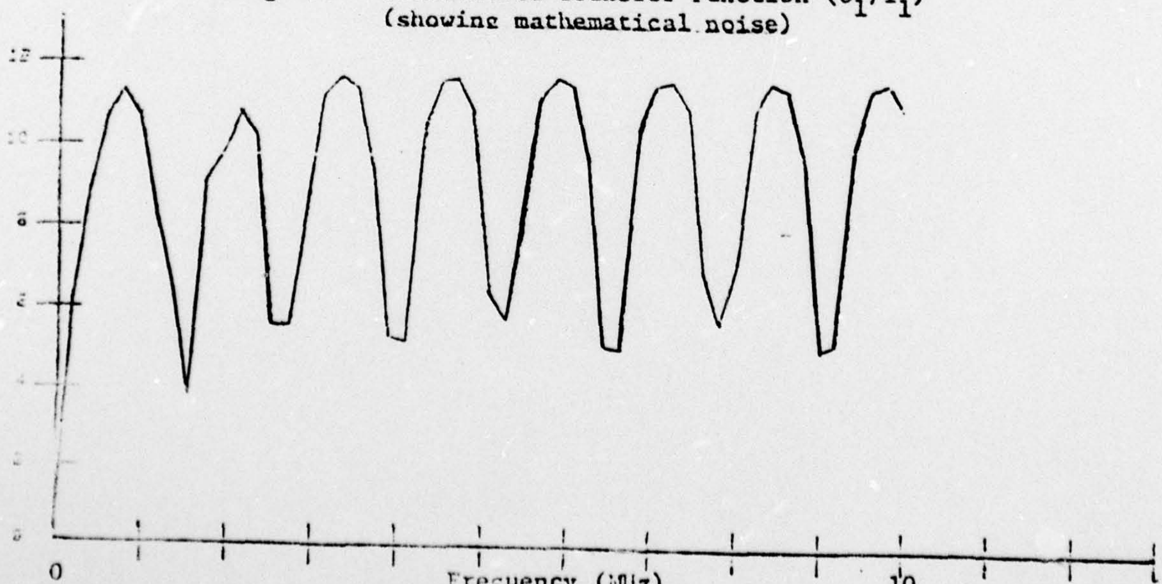


Fig. 9c - Deconvolved Transfer Function (O_2/I_2)
(showing mathematical noise)

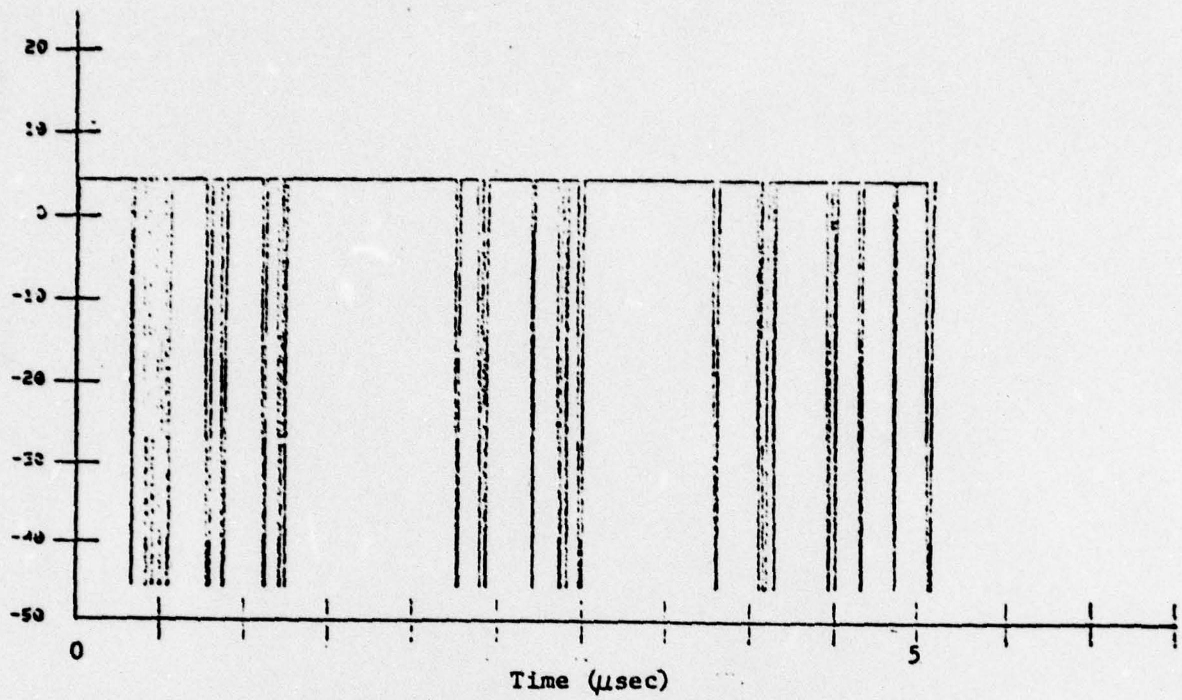


Fig. 10a - Sample Noise 1

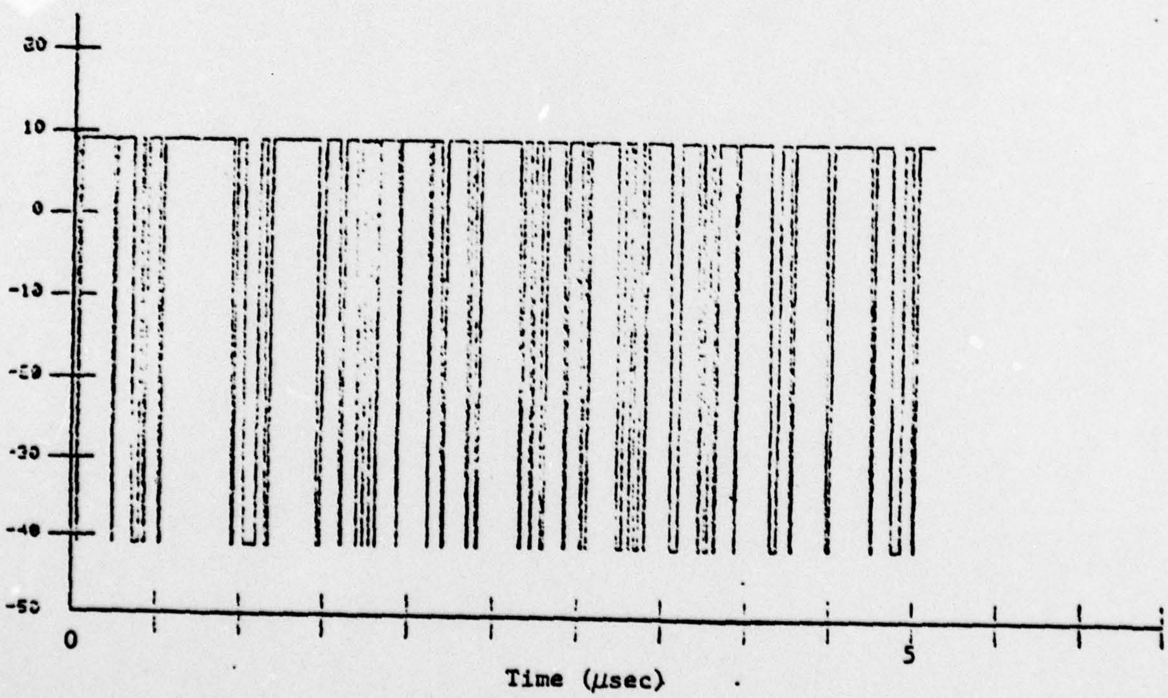


Fig. 10b - Sample Noise 2

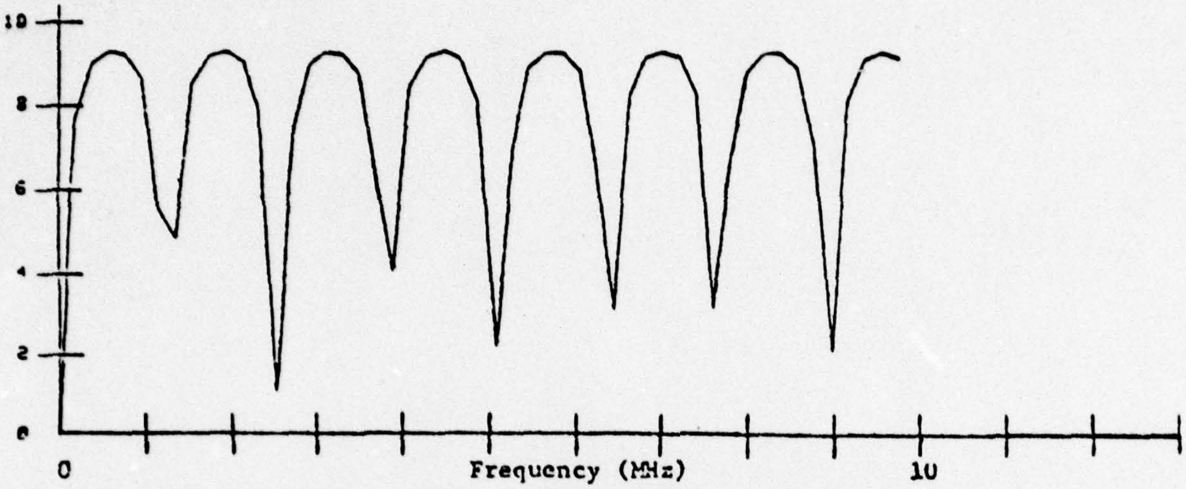


Fig. 11a - Theoretical Transfer Function for a Sample Layered Media Problem

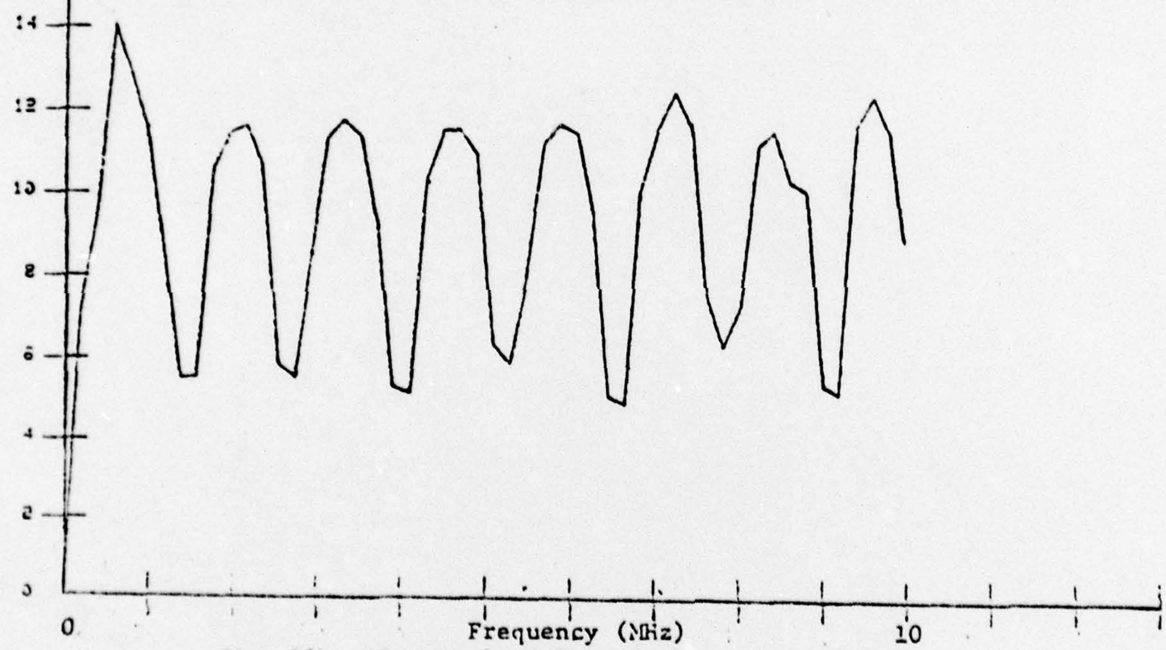


Fig. 11b - Deconvolved Transfer Function (O_1/I_1)
(showing system noise)

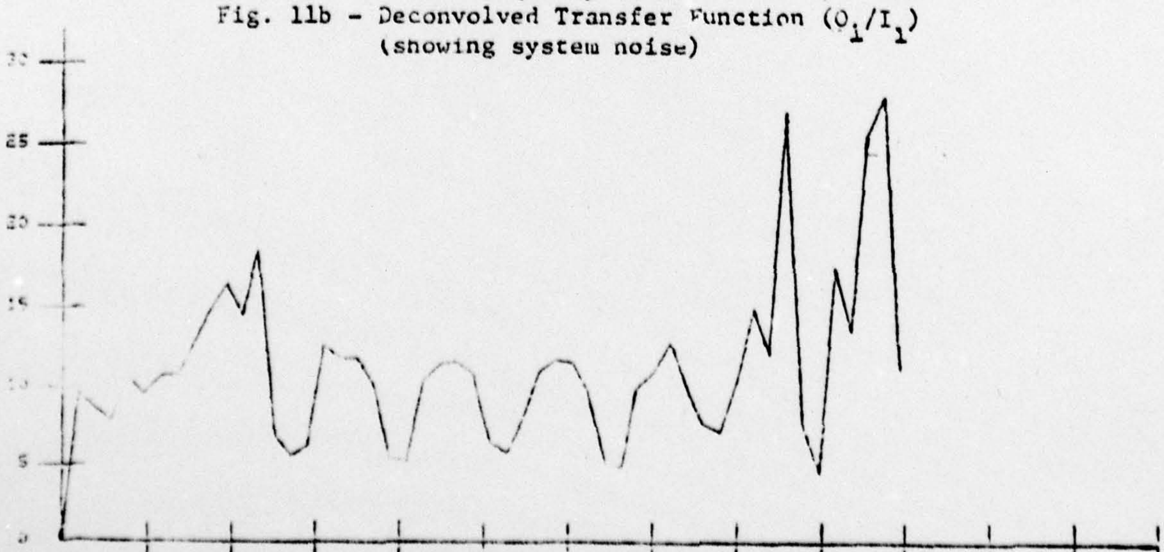


Fig. 11c - Deconvolved Transfer Function (O_2/I_2)
(showing system noise)

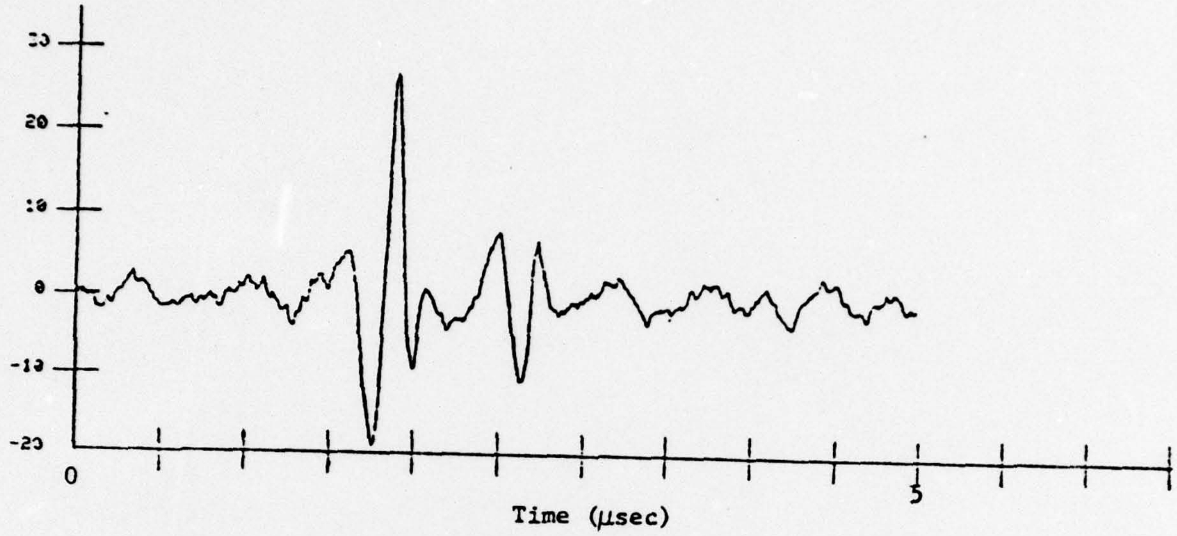


Fig. 12a - Deconvolved Result with Noise
(making Output Function Two look like Output Function One)

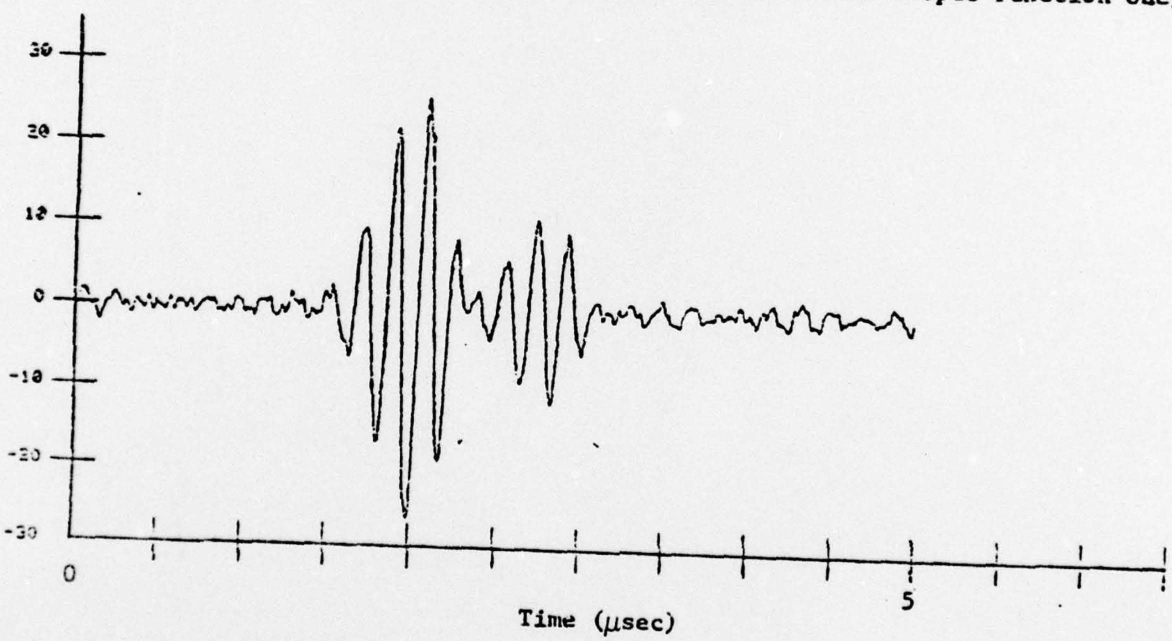


Fig. 12b - Deconvolution Result with Noise
(making Output Function One look like Output Function Two)

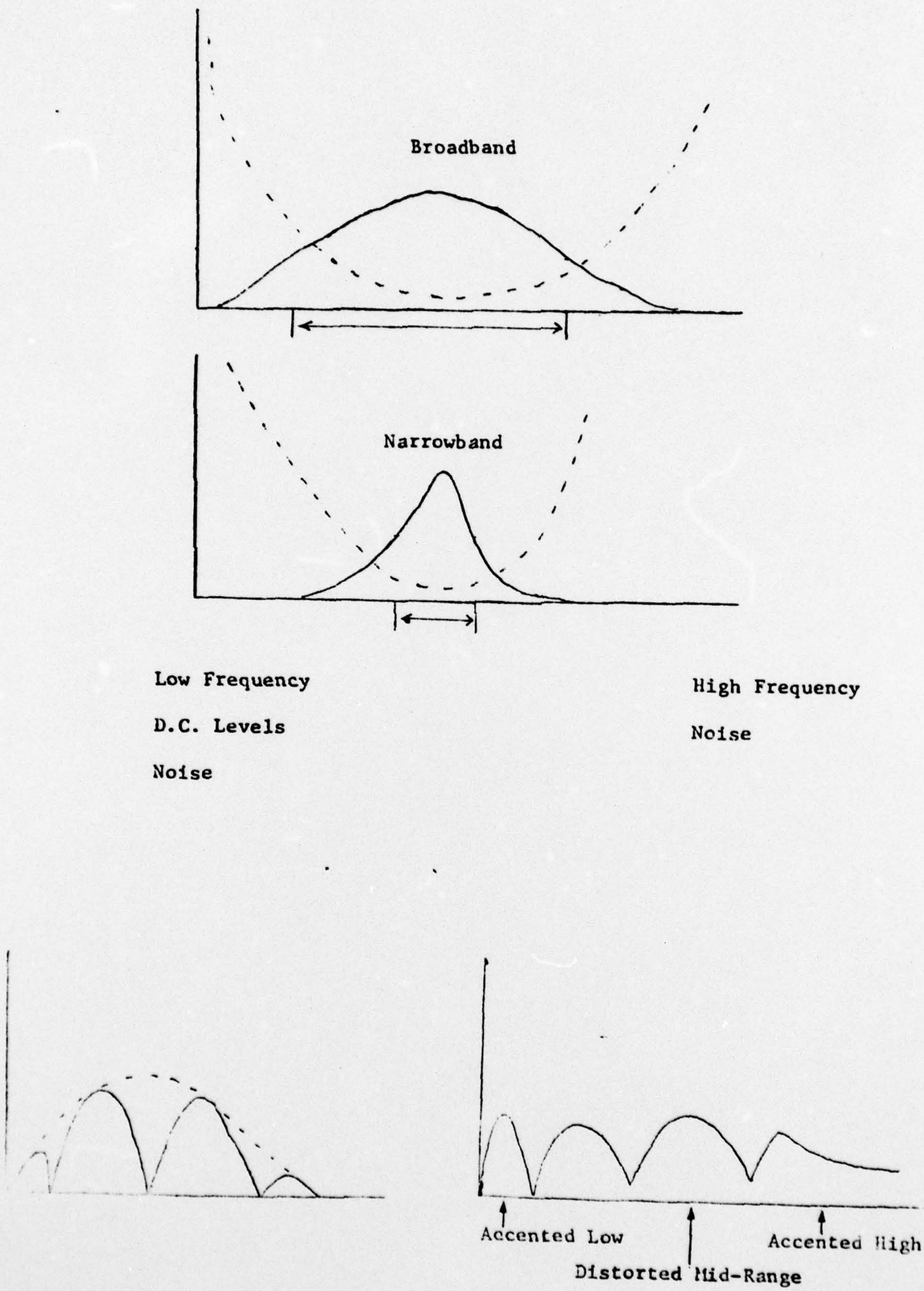


Fig. 13 - Illustration of the Deconvolution Process

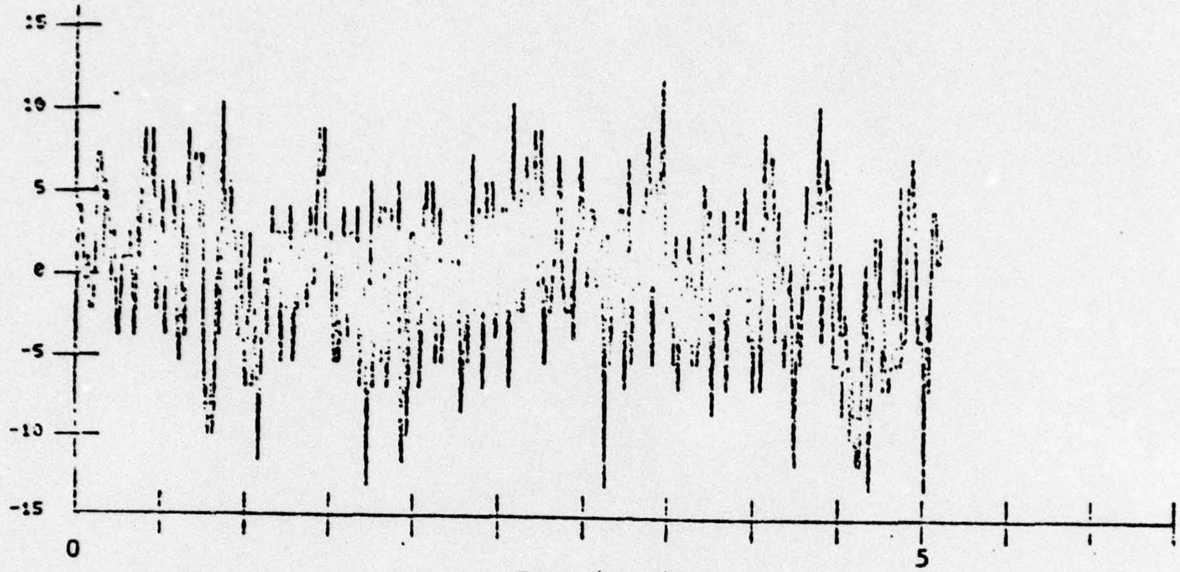


Fig. 14a - Sample of Averaged Noise 1

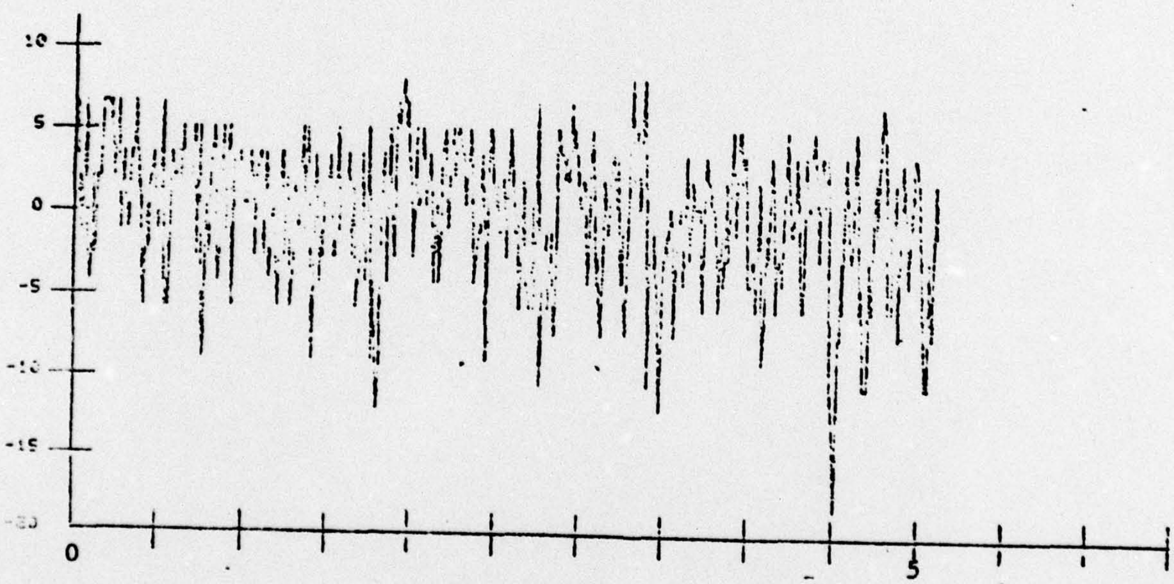


Fig. 14b- Sample of Averaged Noise 2

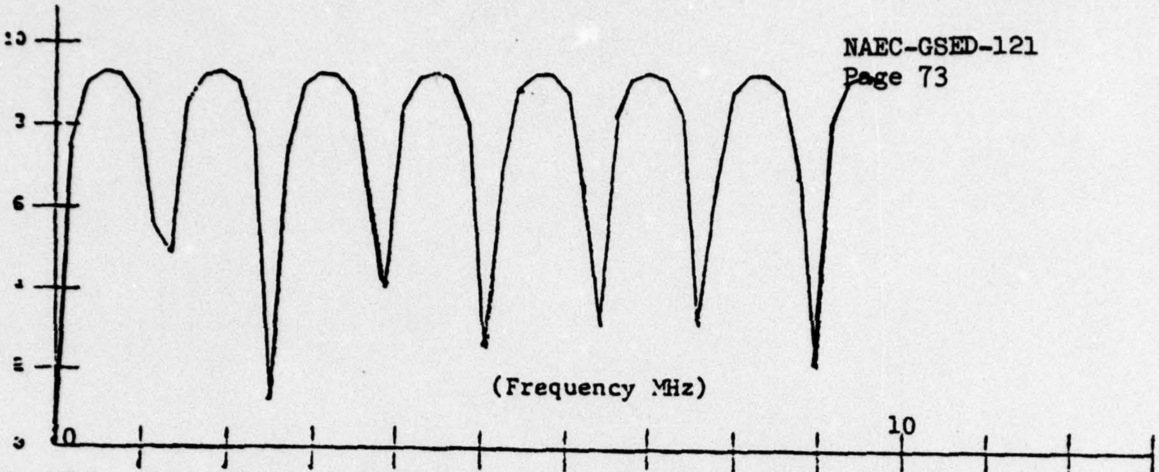


Fig. 15a - Theoretical Transfer Function for a Sample Layered Media Problem

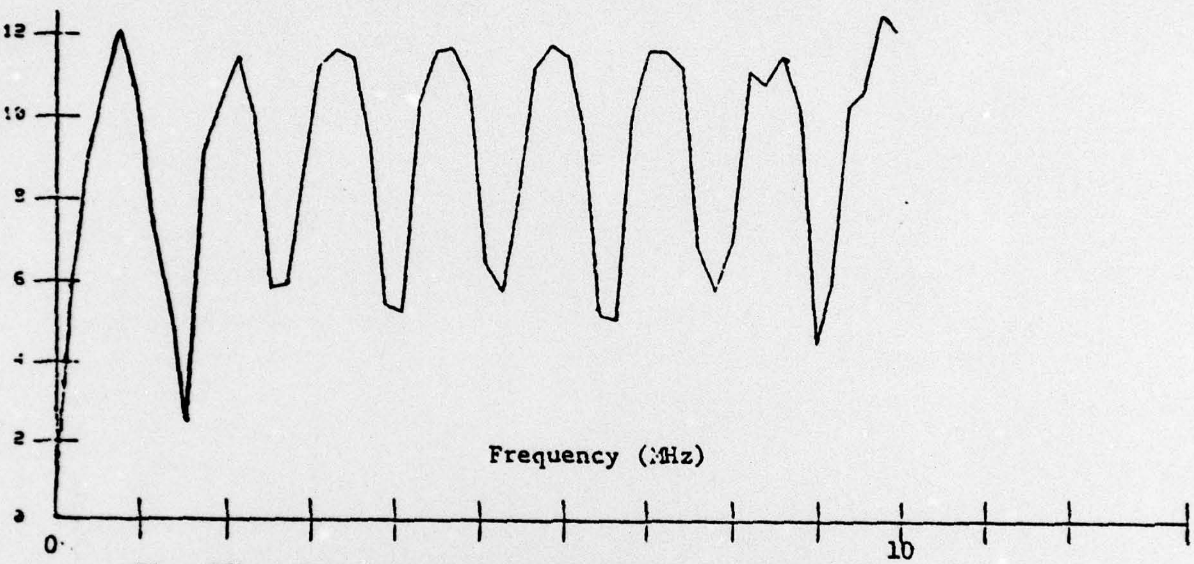


Fig. 15b - Deconvolved Transfer Function (O_1/I_1)
(showing averaging effect on noise)

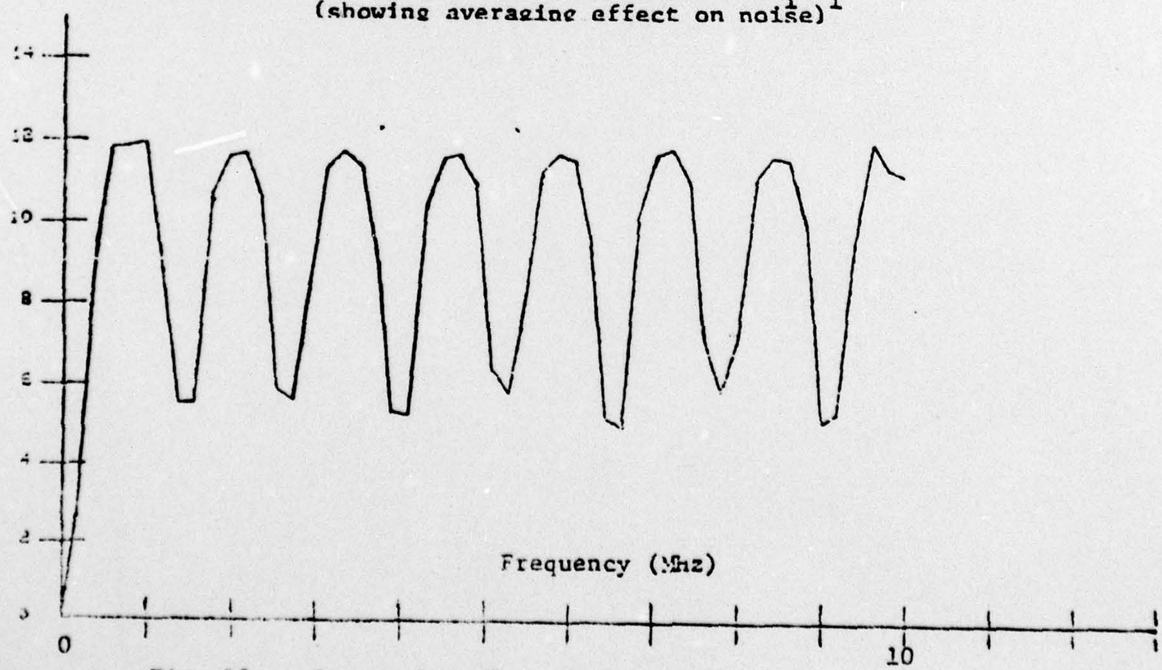


Fig. 15c - Deconvolved Transfer Function (O_2/I_1)
(showing averaging effect on noise)

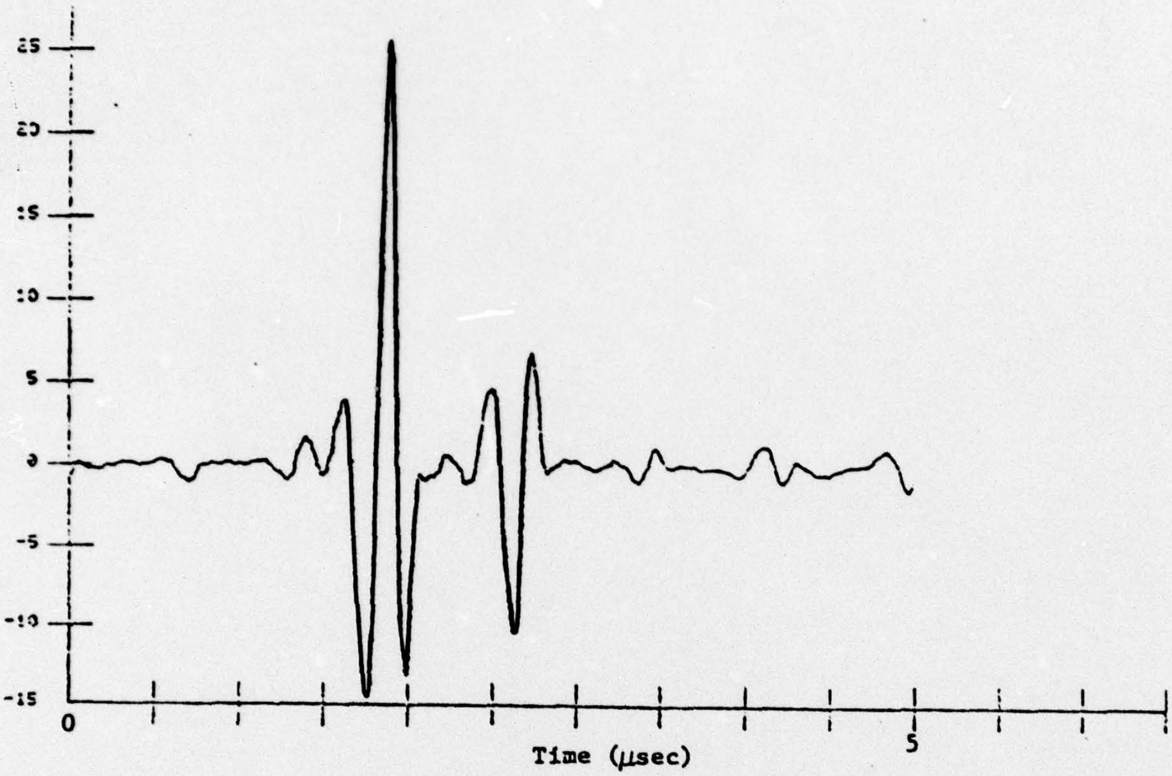


Fig. 16a - Deconvolved Result with Averaged Noise
(making Output Function Two look like Output Function One)

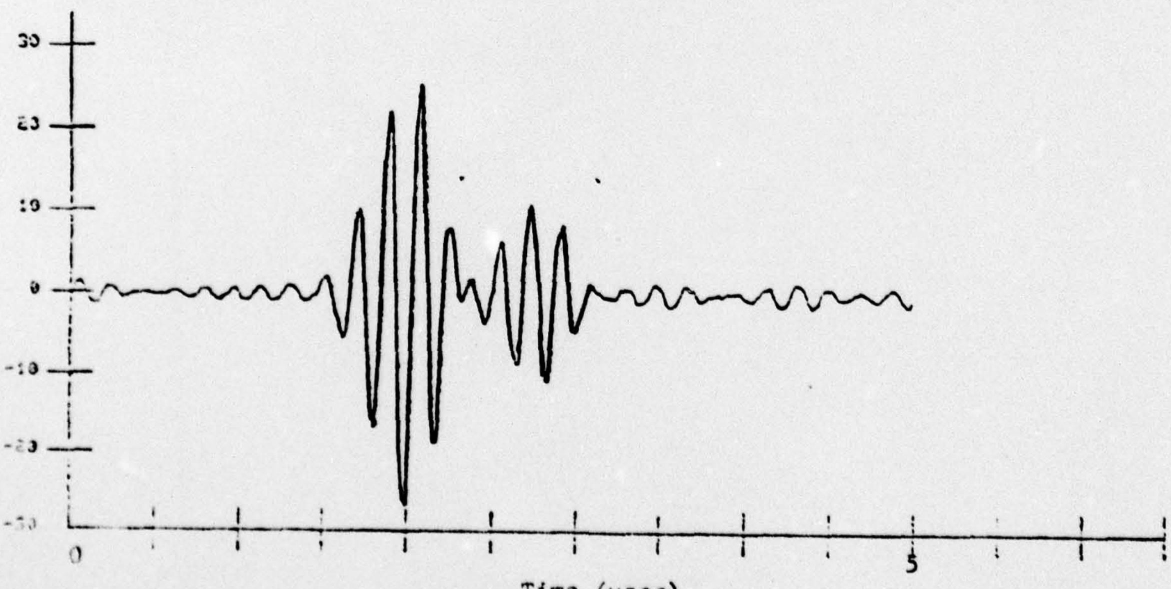


Fig. 16b - Deconvolved Result with Averaged Noise
(making Output Function One look like Ouput Function Two)